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Analysis Method of Module Type Crash Cushion

모듈형태의 충격흡수장치 해석방법

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요 지

도로변에는 다양한 부정형의 구조물들이 방호되지 않은 채 노출되어 있어서 통행차량에 큰 위험요소가 되고 있다. 이러한 부정형 구조물을 효과적으로 방호하는 수단으로 구조물 앞에 에너지흡수형 모듈을 적층구조로 쌓는 방법이 있다. 본 논문은 EPS블록으로 구성된 모듈타입의 충격흡수장치를 차량과 충격흡수장치간의 에너지 평형원리를 이용하여 해석하는 방법을 소개하고 0.9ton-50km/h, 0.9ton-60km/h and 0.9ton-70km/h의 충돌조건에 대한 수치 예제로 설명하였다. 이 방법은 최대가속도, 충돌변형에 걸리는 시간, 모든 모듈에 대한 변형이 완료되기 전에 차량의 완전한 정지여부 등에 대한 예측을 가능하게 하지만, 모듈 수만큼의 매우 듬성듬성한 속도 및 가속도 데이터를 주기 때문에 RA와 OIV같은 안전지수를 구하기 위해서는 보간법을 이용한 데이터 수의 확대가 필요하다. 선형 및 스플라인 보간법을 이용하여 안전도를 분석하고 결과를 비교 분석하였다.

핵심용어: 비정형구조, 모듈, 쿠션, 에너지 평형, 보간

Abstract

Many atypical structures on the roadside are exposed to traffics unshielded posing great danger. One way to shield an atypical structure to secure the occupant safety is to stack energy absorbing material modules in front of the structure. This paper presents the analysis method of module type crash cushion made of EPS blocks using simple energy balance of the car and crash cushion and numerical examples for 0.9ton-50km/h, 0.9ton-60km/h and 0.9ton-70km/h impact are presented. This method gives simple estimation of maximum acceleration, time of crash, whether or not the vehicle stops completely before whole cushion is being crushed. However, since the acceleration and velocity data from the analysis is so crudely spaced that calculation of safety indices such is RA and OIV is not possible. Problem is overcome by using data interpolation. The spline and linear interpolation is introduce and safety analysis is made and the results are compared.

Keywords : atypical structure, module, cushion, energy balance, interpolation

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1. INTRODUCTION

Crash Cushion is used primarily to safely stop an errant vehicle within a relatively short distance. Most of the crash cushions being used today are for the end of the rigid safety shape barrier or for gore areas. Yet there are many atypical structures left unshielded posing potential danger to the traffics when they hit to the structures. One way to shield an atypical structure to secure the occupant safety of an impact vehicle is to stack energy absorbing material modules in front of the structure. To be applicable to a cushion system, material must have enough energy absorbing capabilities while satisfying the safety requirements of the vehicle occupant. Static tests were performed for candidate materials as modules such as Quard-Guard system module, sand bag, recycled tires, Geo-Container, Geo-Cell and Expanded Polystyren (EPS) Blocks and showed that EPS block of 30kg/cm^3 density is a good material for module type crash cushion (Ko, et al 2007). To check the dynamic effect of EPS block drop tests have been made with impact speed up to 35.6km/h. Drop test results were compared with static test results and no appreciable difference were found. To improve the module property of the 30Kg/cm^3 EPS block, putting void holes to the block is suggested and drop test are performed for the blocks with holes.

2. Module by Module Analysis (MMA)

This method is based on individual modules acting independently with relation to each other(Marquis, 1975). The principal factors that reduce the kinetic energy are (1) energy absorbed by the spring action of the crash cushion, (2) fiction of the crash cushion moving over the road surface.

Significant quantity of energy may be absorbed by the vehicle, which is neglected in this study.

The kinetic energy of the vehicle can be expressed as ;

$$(KE)_o = \frac{W_o V_o^2}{2g} \qquad (1)$$

where W_o = the vehicle weight,
V_o = the impact velocity
g = the acceleration due to gravity.

The crash cushion may be idealized as in Fig.1(a). In the model, assumption is made that only one spring compresses at a time, which was found to be reasonably correct by high speed photos of the test.(L.C. Bank and T.R. Gentry, 2001) This neglects the time interaction of the springs. Fig.1(b), (c) shows the gradual compression of the modules.

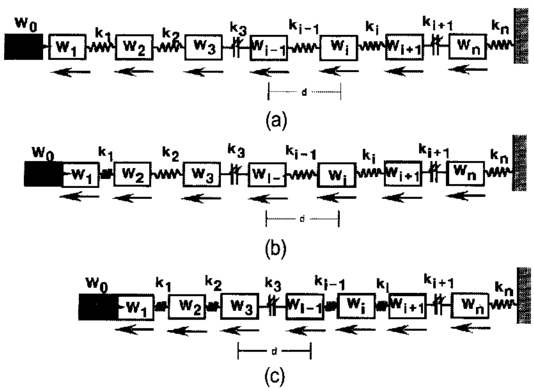

Fig 1. Successive Compression of Modules

When a vehicle hits a crash cushion and the first cushion is compressed, the resulting change in kinetic energy of the vehicle is expressed as;

$$(\Delta KE)_{spring} = Fd/2 \qquad (2)$$

where, F = the maximum force on the spring
d = the distance spring is compressed

Also, using spring constant k, maximum force F can be written as $F = kd$, which leads to the following equation.

$$(\Delta KE)_{spring} = Fd^2/2 \quad \text{(Elastic Spring)} \qquad (3)$$

In addition to the energy absorbed by the spring, energy is lost by the friction of the module on the surface. If we make an assumption that the weight is distributed over the length of the module and the average distance of the first module movement will be approximately equal to one-half of the compressed distance, and that spring works as rigid-perfectly plastic one with resisting force F_p , change in kinetic energy while spring is compressed can be written as;

$$(\Delta KE)_{spring} = F_p d \text{ (Plastic Spring)} \qquad (4.1)$$

$$(\Delta KE)_{friction} = Wd\mu / 2 \qquad (4.2)$$

where, W = theweight of the Crash Cushion module,

μ = the friction coefficient.

Therefore, energy absorbed by the crush of the first module for plastic and elastic case can be written as ;

$$(\Delta KE)_1 = k_1 d_1^2 / 2 + W_1 d_1 \mu / 2 \text{ (Elastic)} \qquad (5.1)$$

$$(\Delta KE)_1 = F_{p1} d_1 + W_1 d_1 \mu / 2 \text{ (Plastic)} \qquad (5.2)$$

In general, energy absorbed by the crush of the n-th module for plastic and elastic case can be written as;

$$(\Delta KE)_n = k_n d_n^2 / 2 + (\sum_{i=1}^{n-1} W_i + W_n / 2) \mu d \text{ (Elastic)} \qquad (7.1)$$

$$(\Delta KE)_n = F_{pn} d_n + (\sum_{i=1}^{n-1} W_i + W_n / 2) \mu d \text{ (Plastic)} \qquad (7.2)$$

If the effect of the additional weight of the modules on the velocity of the vehicle is neglected and crush characteristics of each module are the same, the total energy that may be absorbed by a crash cushion of n number of module is generalized as;

$$KE = \sum_{i=1}^{n} (\Delta KE)_i = nkd^2/2 + (\sum_{i=1}^{n} \frac{2i-1}{2} W) \mu d \text{ (Elastic)} \qquad (8.1)$$

$$KE = \sum_{i=1}^{n} (\Delta KE)_i = nF_p d + (\sum_{i=1}^{n} \frac{2i-1}{2} W) \mu d \text{ (Plastic)} \qquad (8.2)$$

From the above relations, vehicle velocity before the i-th module started being crushed can be calculated as follows;

$$KE_i = KE_{i-1} - kd^2/2 - (\sum_{i=1}^{n-1} W_i + W_n / 2) \mu d \text{ (Elastic)} \qquad (9.1)$$

$$KE_i = KE_{i-1} - F_{p(i-1)} d_{(i-1)} - (\sum_{i=1}^{n-1} W_i + W_n/2) \mu d \text{ (Plastic)} \qquad (9.2)$$

$$V_i = \sqrt{\frac{2gKE_i}{W_0 + iW}} \qquad (10)$$

Also, average acceleration during the movement of d_i can be written as;

$$G_i = \frac{V_{i-1}^2 - V_i^2}{2gd} \qquad (11)$$

Equations 9.1, 9.2, and 10, 11 can be used to calculate the vehicle velocity and average acceleration as crash proceeds module by module. The limitation of the energy balance method is that neither the acceleration change during the crush of one module, nor the time history of the velocity and acceleration of impact vehicle can be found. But, neglecting the acceleration variation within the crush of one module and using the relationship between the crush distance and velocity, acceleration and time, time history of acceleration and velocity can be approximated.

If S_i represents the crush distance of i-th module, it can be written as follows;

$$S_i = v_i t_i + 1/2 a_i t_i^2 \text{, where } a_i = G_i g \qquad (12)$$

which leads to,

$$t_i = \frac{-v_i + \sqrt{v_i^2 + 2a_i S_i}}{a_i} \qquad (13)$$

Using Eq.13, total time elapsed before crushing of i-th module finishes can be calculated as follows;

$$t = t_i + \sum_{i=1}^{n-1} t_i \qquad (14)$$

Now, time history of velocity, acceleration and deformation can be obtained. But data points in this kind of time history has too sparse to calculate the safety indices such as Ridedown Acceleration(RA) and Occupant Impact Velocity(OIV). This is attributable to the fact that number of data points are equal to the numbers of module. This can be overcome by the interpolation method. In this study, built-in interpolation function of MATLAB (Mathwork, 1998), INTERPL and SPLINE are considered. INTERPL calculates the data between the data points using linear interpolation method, while SPLINE uses spline method. Out of the two method, SPLINE gives smoother curve, but sometimes it exaggerates the velocity and acceleration-time history even after the occupant hits the vehicle.

3. Safety Index Calculation

In the next chapter resistive type crash cushion composed of EPS block modules will be analysed by energy method explained and safety indices will be calculated.

In evaluating safety performance of roadside safety features, threshold index value human can sustain is calculated from the measured acceleration-time history. NCHRP Report 230 (Michie,1981) explained about the two safety indices, OIV(Occupant Impact Velocity) and RA(Ridedown Acceleration) which was used in current US performance evaluation NCHRP Report 350 (Ross, 1993) and was referred by European Committee for Normalization (CEN, 1977) and Korean Design Guide (MOCT, 1998).

Following is how the indices OIV and RA are calculated according to NCHRP Report 350.

The performance design strategy for a feature should be to (1) keep the occupant-vehicle interior impact velocity low by minimizing average vehicle accelerations or vehicle velocity change during the time the occupant is traveling through the occupant space and (2) limit peak vehicle accelerations during occupant ridedown.

The expression for occupant impact velocity is

$$V_{I_{xy}} = \int_0^{t^*} a_{x,y} dt \qquad (15)$$

Where $V_{I_{xy}}$ is occupant-car interior impact velocity in the x or y directions, $a_{x,y}$ is vehicular acceleration in x or y direction, and t^* is the time when the occupant has traveled either 0.6m forward or 0.3m lateral, whichever is smaller. Time t^* is determined by incremental integration as follows:

$$X, Y = \int_0^{t^*}\int_0^{t^*} a_{x,y} dt^2 \qquad (16)$$

Where, X = 0.6m and Y = 0.3m. Acceleration in the x direction is integrated twice with respect to time to find the value of time, t_x^*, at which the double integration equals 0.6m. Acceleration in the y direction is integrated twice with respect to time to find the value of time, t_y^*, at which the double integration equals 0.3m. Time t^* is the smaller of t_x^* and t_y^*.

For the ridedown acceleration to produce occupant injury, it should have at least a minimum duration ranging from 0.007 to 0.04 sec, depending on body component (Snyder 1970). Thus, vehicular acceleration "spikes" of duration less than 0.007s are not critical and should be averaged from the pulse. An arbitrary duration of 0.010s has been selected as a convenient and somewhat conservative time base for averaging accelerations for occupant risk assessment. This is accomplished by taking a moving 10-ms average of vehicular "instantaneous" accelerations in the x and y directions, subsequent to t*.

The OIV and RA is equivalent to THIV(Theoretical Head Impact Velocity) and PHD(Post-impact Head Deceleration) of CEN and Korean Design Guide if yawing effects are not considered. In Korean Design Guide, limiting values are set as 12.2m/sec and 20g for THIV(OIV) and PHD(RA) respectively, which will be used in this study.

4. Analysis

Ko, et.al. performed statics and drop tests for the Expanded Polystyrene Blocks. Analysis of the drop test showed that 450◊450◊300 EPS block with 9 holes had resisting force of around 5000kg when it was assumed as rigid perfectly plastics spring. The unit weight of the module was 1.8225kg and crush ratio was about 0.8. Using this data crash cushion composed of 9 EPS blocks is analysed by MMA for 0.9ton-80km/h and 0.9ton-60km/h impact and safety analysis is performed.

Fig.2. is the result of MMA when a 0.9ton vehicle hits a crash cushion made of 9 numbers 450 × 450 × 300 EPS block module by the impact speed of 50km/h. Analysis was made by Matlab following the routine explained in Chapter 2. The algorithm is simple enough to be solved by spread sheet, which is one of the strength of energy method. From the figure, it can be seen that vehicle velocity reduces to 0 after the crush of 5th EPS module, and the maximum acceleration is as small as 3.9g, and 0.24 second elapses for the vehicle to stop completely. From the results of MMA analysis in Fig.2 it is understandable that, even estimation can be made about maximum acceleration, time of crush, whether or not the vehicle stops completely before whole length of the cushion is being crushed, it is not possible to calculate the safety indexes such as RA and OIV, since acceleration and velocity data are so crudely spaced.

i	di(m)	fk(kg)	wt(kg)	ke(kg-m)	v(m/sec)	a(g)	t(sec)
0	0	0	0	8859.1	13.89	0	0
1	0.45	5000	1.8225	7283.9	12.582	3.9257	0.033998
2	0.45	5000	1.8225	5708.3	11.127	3.9109	0.071958
3	0.45	5000	1.8225	4132.3	9.4577	3.8962	0.11568
4	0.45	5000	1.8225	2555.8	7.4306	3.8815	0.16897
5	0.45	5000	1.8225	979	4.5942	3.867	0.24382
6	0.45	5000	1.8225	0	0	2.3931	0.43972
7	0.45	5000	1.8225				
8	0.45	5000	1.8225				
9	0.45	5000	1.8225				

Fig. 2 Calculation of 'v' and 'a' (0.9ton-50km/h)

Fig.3 is the result of the impact case of the 0.9ton vehicle to the same cushion but with impact speed of 60km/h. For this case, vehicle stops after the crushing the 8th EPS module and crushing time is close to 0.39 sec.

i	di(m)	fk(kg)	wt(kg)	ke(kg-m)	v(m/sec)	a(g)	t(sec)
0	0	0	0	12757	16.668	0	0
1	0.45	5000	1.8225	11182	15.589	3.9452	0.027901
2	0.45	5000	1.8225	9606.3	14.435	3.9303	0.057877
3	0.45	5000	1.8225	8030.3	13.184	3.9155	0.090463
4	0.45	5000	1.8225	6453.9	11.808	3.9007	0.12647
5	0.45	5000	1.8225	4877	10.254	3.8861	0.16727
6	0.45	5000	1.8225	3299.8	8.4261	3.8716	0.21545
7	0.45	5000	1.8225	1722.1	6.0811	3.8571	0.27749
8	0.45	5000	1.8225	144.02	1.7568	3.8427	0.39231
9	0.45	5000	1.8225	0	0	0.34994	0.9046

Fig. 3 Calculation of 'v' and 'a' (0.9ton-60km/h Impact)

Fig.4 shows the time history of acceleration(a_i, □), vehicle velocity (v_i, ○) and deformation (s_i, ∗) of an impact vehicle of 0.9ton-60Km/h impact to the crash cushion made of 9 EPS blocks of 450 × 450 × 300, which results total cushion length to be 0.45 × 9=4.05m. The marks in the figure represent the data points of Fig.3 and the solid lines represent connecting the data points linearly interpolating the points by 0.001 sec interval. The dotted lines represent the data points interpolated by spline with the same interpolation points. This example shows a problem relating to the spline interpolation method from the sparse data points. In the figure, it can

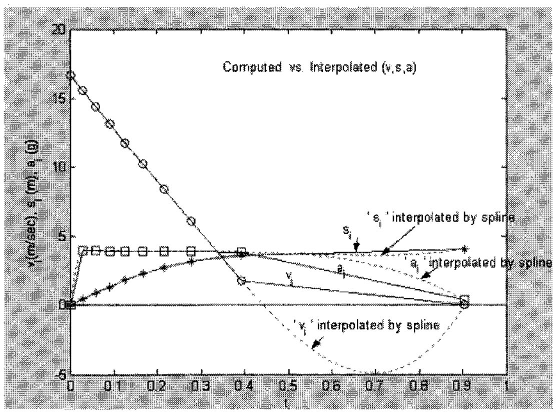

Fig. 4 Spline and Linear Interpolation(0.9ton-60km/h)

be seen that spline interpolation magnifies vehicle velocity and acceleration considerably between 0.4sec and 0.9sec compared to linearly interpolated velocity and acceleration.

Fig.5(a) shows the safety analysis based on the time history of Spline interpolated data of Fig.4 acceleration using spline interpolation and Fig.5(b) is based on the linear interpolated acceleration data of Fig.4

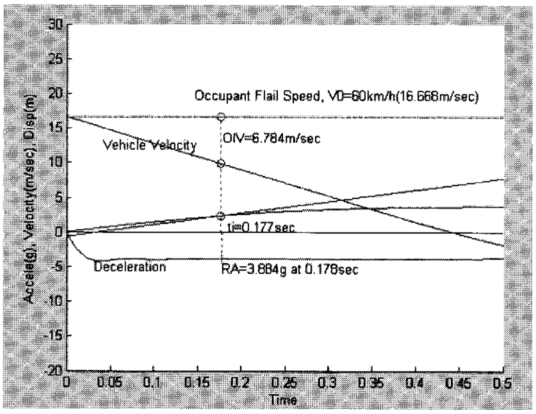

Fig. 5(a) Safety Analysis : Spline Interpol. (0.9ton-60km/h Impact)

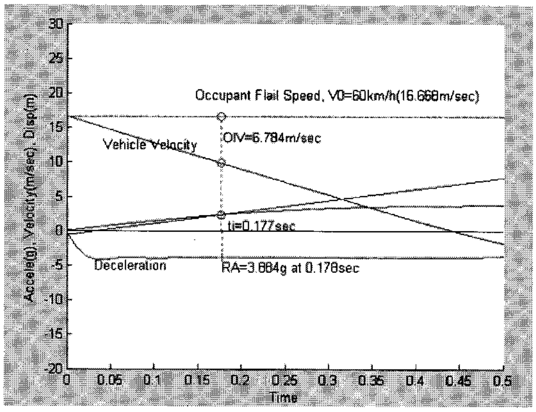

Fig. 5(b) Safety Analysis : Linear Interpol. (0.9ton-60km/h Impact)

Safety indices four the two Figures are summarized in Table 1.

Looking at the table, interpolation method does not seem to have a significant effect on the safety indices. However, it should not be generally accepted. In the

Table. 1 Safety Index Comparison for Interpolation Method (0.9ton-60km/h Impact)

Interpolation	Impact time t_i	OIV	RA
Spline(Fig.5(a))	0.177(sec)	6.784(m/sec)	3.884g(@0.178sec)
Linear(Fig.5(b))	0.176(sec)	6.745(m/sec)	3.882g(@0.177sec)

figure, vehicle velocity or relative impact velocity is not different between interpolation methods chosen 0.177sec when the secondary impact happened. This resulted almost the same OIV values. Also, after the secondary impact, maximum acceleration happens at the proximity of the secondary impact time for both interpolation methods that no difference in RA values between the interpolating method is observed.

To understand the significance of interpolation method on the safety index calculations, another example is presented in Fig.6(a). It is the result of analysis when a 0.9ton vehicle hits a crash cushion made of 9 standard

i	di(m)	fk(kg)	wt(kg)	ke(kg-m)	v(m/sec)	a(g)	t(sec)
0	0	0	0	17364	19.446	0	0
1	0.45	5000	1.8225	15789	18.524	3.9682	0.023703
2	0.45	5000	1.8225	14213	17.558	3.9532	0.048646
3	0.45	5000	1.8225	12637	16.539	3.9383	0.075041
4	0.45	5000	1.8225	11061	15.458	3.9235	0.10317
5	0.45	5000	1.8225	9483.8	14.299	3.9087	0.13341
6	0.45	5000	1.8225	7906.5	13.043	3.8941	0.16633
7	0.45	5000	1.8225	6328.8	11.658	3.8795	0.20277
8	0.45	5000	1.8225	4750.8	10.09	3.8651	0.24415
9	0.45	5000	1.8225	3172.3	8.237	3.8507	0.29326

Fig. 6(a) Calculation of 'V' and 'a' (0.9ton-70km/h Impact)

i	di(m)	fk(kg)	wt(kg)	ke(kg-m)	v(m/sec)	a(g)	t(sec)
0	0	0	0	17364	19.446	0	0
1	0.45	15000	1.8225	12639	16.574	11.73	0.024986
2	0.45	5000	1.8225	11063	15.491	3.9375	0.053055
3	0.45	5000	1.8225	9487	14.33	3.9227	0.083235
4	0.45	5000	1.8225	7910.6	13.073	3.9079	0.11608
5	0.45	5000	1.8225	6333.8	11.686	3.8933	0.15243
6	0.45	5000	1.8225	4756.5	10.116	3.8787	0.19371
7	0.45	5000	1.8225	3178.8	8.262	3.8642	0.24268
8	0.45	5000	1.8225	1600.8	5.8571	3.8498	0.30642
9	0.45	5000	1.8225	22.281	0.69033	3.8355	0.44388

Fig. 6(b) Improving Energy Absorbing Capacity by Increasing the Resisting Force of Module 1 (0.9ton-70Km/h Impact)

EPS block modules by 70km/h impact speed. In the impact, after the whole modules were crushed thoroughly, vehicle speed of 8.237m/sec still remains as the upper Fig.6(a) shows. To attenuate the impact energy completely, designer should either increase the length of the crash cushion, i.e. stack more modules, or change the mechanical property of the modules. Fig.6(b) shows the way of improving energy absorbing capability by increasing the ultimate force of a module instead of increasing the number of module i.e, system length. Fig.6(b) is the analysis result when the ultimate force F_p is increased from 5000kg to 15000kg and other conditions are kept the same. The modified EAD absorbs almost all the kinetic energy of the vehicle with just 0.69m/sec velocity remaining.

Fig.7 shows the time history of acceleration(a_i, □), and vehicle velocity(v_i , ○) of a 0.9ton-70km/h vehicle impact to a modified crash cushion explained in Fig.6(b). Each mark point in the figure are the calculation point of Fig.6(b). The black solid line in the figure, represents the points interpolated between the data points by linear interpolation and the dotted line represents the points by spline interpolation. This figure manifests the different effects two interpolation methods give on to the safety index calculations.

When the spline interpolation is used, acceleration and velocity time history is greatly magnified compared to the result of linear interpolation resulting in maximum difference in velocity 17.5m/sec and acceleration 23.5g respectively. This difference happened after 0.4sec when the data points from the energy method is very sparse. Before 0.4sec, there are no notable differences between the interpolation methods except that spline interpolation give the smoother curves.

Fig.8(a) shows the safety analysis based on the spline interpolation in Fig.7 and Fig.8(b) is based on the linear interpolated in time of acceleration data of Fig.7.

Also, of note in Fig.6(b) is that increasing the ultimate force of module No.1 significantly increased the

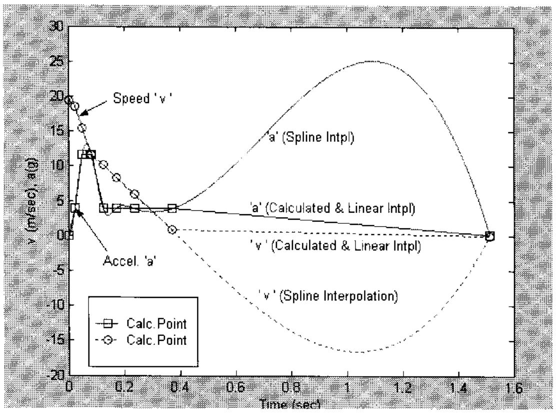

Fig.7 Spline and Linear Interpolation (0.9ton-70km/h)

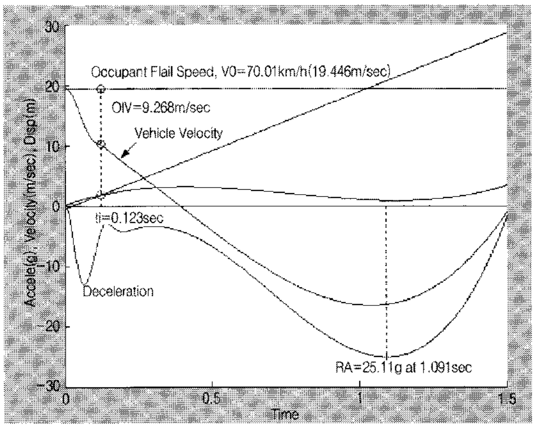

Fig. 8(a) Safety Analysis
(Spline Interpolation, 0.9ton-70km/h Impact)

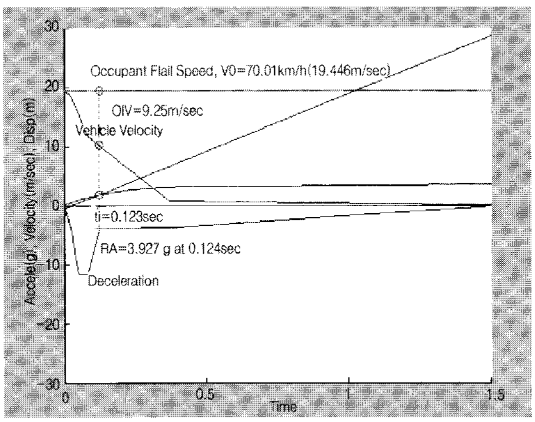

Fig. 8(b) Safety Analysis
(Linear Interpolation, 0.9ton-70km/h Impact)

acceleration at 0.025sec. Safety indices from the Fig.8(a) and Fig.8(b) are summarized in Table 2. Depending on the Spline method RA values differ opprecially that special care must be taken. From the result, it can be concluded that if MMA is used for the safety index calculation, proper interpolation must be chosen and linear interpolation is preferred to spline interpolation.

Table. 2 Safety Index Comparison for Interpolation Method (0.9ton-70km/h Impact)

Interpolation	Impact time t_i	OIV	RA
Spline(Fig.8(a))	0.123(sec)	9.268(m/sec)	25.11g(@1.091sec)
Linear(Fig.8(b))	0.123(sec)	9.250(m/sec)	3.93g(@0.124sec)

5. Conclusion

Analysis method of the module type crash cushion using energy balance is introduced and numerical examples for 0.9ton-50km/h, 0.9ton-60km/h and 0.9ton-70km/h impact are presented. The analysis method is simple to use but produces only one velocity or acceleration value per one module. Since the velocity and acceleration data are so crudely given at the module points, safety analysis needs refined data point through interpolations. Safety analysis using linear and spline interpolation are made and compared. Spline interpolation results in overly exaggerated accelerations between the last two data points leading to an unrealistically high value of Ridedown Acceleration. Linear interpolation between data points calculated from the module by module analysis is recommended for safety analysis.

감사의 글

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