The crash severity indicator — theoretical background and performance in real world crashes.

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ABSTRACT

In the field of traffic safety it is essential that estimation of crash severity from real world accidents can be made with sufficient precision. Systematic as well as random errors in crash severity estimation together with other types of errors in the response of the accident forces makes the possibility to draw conclusions from accident data limited. It is therefore important to reduce different kinds of errors.

In this paper a crash severity indicator which can be mounted into cars is presented. The indicator is a low cost mechanical device that can measure the deceleration in an accident, and under some conditions, also the velocity change (delta-v). The theoretical background is described as well as the results of some full-scale barrier tests with severity indicators mounted into the test cars.

It is concluded that the severity indicator can give a fairly high precision and together with other types of data collected will give valuable information for a low cost. The indicator is already mounted into rearward-facing child restraints used among the public.

Background

One of the most important factors when classifying an accident is the severity. Accident severity can however be defined and measured in many different ways. Several ways have been proposed especially for frontal collisions, such as delta-V, ETS, VDI, mean acceleration etc. It seems however, that none of these ways of measuring accident severity can be used in real world accidents with sufficient precision.

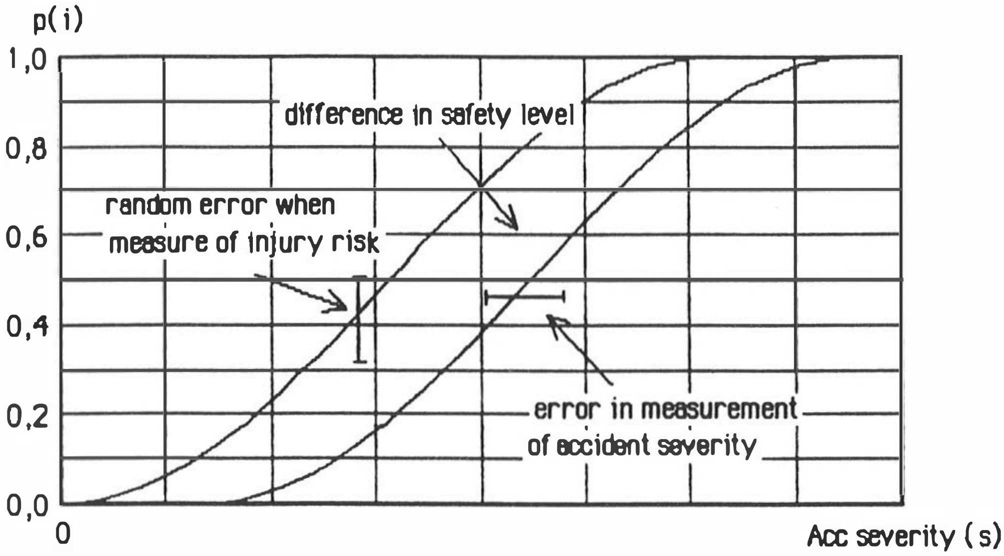
In fig 1 a schematic probability function is showed for two different constructions or cars. It is often of great interest to compare the construction in terms of increased safety. If such a comparison should be possible to conduct, it is essential that both injuries and accident severity can be measured with sufficient precision. The injury variable will certainly include random errors due to ie biological variation, while the measurements of accident severity should include as little errors, both systematic and random, as possible. Otherwise, the possibility to draw conclusions from real world accidents is limited.

It is also of great interest to get a better picture of different accident severity distributions, in order to construct cars that are optimized towards real life.

In this paper, a cheap technical device, construted to decrease errors in measurement of accident severity, is presented. The device can be constructed in a way that it can measure some different characteristics of an accident, depending how it is optimized. In this paper, it was aimed at showing how it can measure mean acceleration and change of velocity.

It is also shown how the device can be mounted into child restraints.

Fig 1



Schematic probability functions for injury risk for different accident severity.
$t_1(s)$ refers to construction (1) and $t_2(s)$ to construction (2).

Material/Method

This crash recorder is of a cheap mechanical type and measures the crash severity in terms of mean acceleration or ΔV.

The indicator is constructed as a mass-spring system where the maximum displacement is measured by a string. The string is attached to the mass which will pull out till the maximum displacement and then leave it there. The spring and the mass is mounted in a closed tube. The mass has a hole to reduce the effects of viscous damping. In figure 2 there is a side view sketch of the indicator. The string is placed in the slot at the top of the indicator.

To analyze the response of the mass-spring system in different kinds of acceleration curves and how to optimize its construction a simulation model was developed. The equations used is the differential equation for the indicator and the equation for the acceleration of the tube and also the initial conditions for the two equations. From the solution of these equations, we get among other things the displacement of the mass as a function of time.

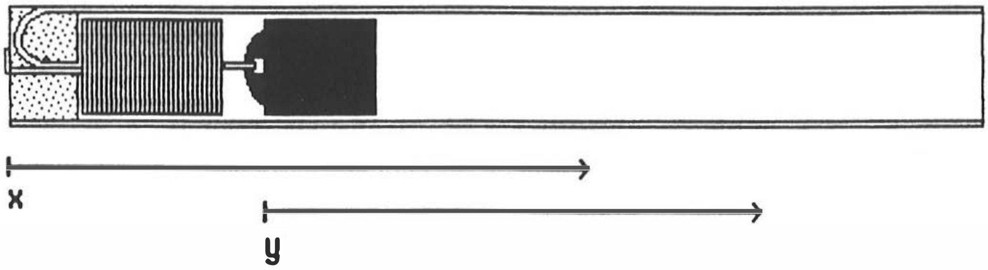
To study the accordance of the simulated response with a response in a real crash two crash tests were made with a sled in which six crash recorders were filmed with a high speed camera. The simulated and the measured displacement of the mass were then compared. Special studies of the spring were made to analyze how it influenced the displacement, for example if it was oscillating during the crash.

When the accordance of the indicator was analyzed there was a serie of five full scale barrier tests made where crash recorders were placed both in child restraints and cars. The maximum displacement of the indicators were then measured and the approximate value of ΔV was calculated. The acceleration of the child restraints and the cars was measured by accelerometers. The results from the simulation model were compared with the real outputs.

The child restraints used were rearward facing seats for group I according to ECE 44 with 3-year old dummies (15 kg). In the front seat, the child restraint was leaning against the clash board, while in the rear seat, the loads were transferred to the floor of the car.

The simulation model
Figure 2 shows the coordinate system of the crash recorder and parameters involved in the equations below.

Fig 2



x = displacement of the tube relatively a fix point
y = displacement of the mass relatively a fix point
$s = y - x$ = displacement of the mass relatively the tube
$m = m_{mass} + m_{spring}/2$ = equivalent mass for the system
c = damping coefficient
k = constant of the spring
F_0 = prestress force of the spring
$F_{\mu ma}$ = frictional drag from the mass
$F_{\mu sp}$ = frictional drag from the spring
$F_{\mu st}$ = frictional drag from the string

The relation between the force of inertia and the external forces acting on the mass is shown in equation 1a. It contains terms for spring force, viscous damping, prestress forces of the spring and also frictional drag from the mass, spring and string. Equation 2 shows the acceleration of the tube.

$$my'' = -c(y'-x') - k(y-x) - F_0 - F_{\mu ma} - F_{\mu sp} - F_{\mu st} \qquad \text{eq 1a}$$
$$x'' = a(t) \qquad \text{eq 2}$$
$$x(0) = y(0) = 0, \quad x'(0) = y'(0) = v_0 \qquad \text{initial conditions}$$

To numerically solve the equations the Euler method is used. If we rewrite eq 1a so the terms concerning the behavior of the mass is on the left and the rest on the right we get equation 1b.

$$y'' + c/m \cdot y' + k/m \cdot y = c/m \cdot x' + k/m \cdot x - F_0 - F_{\mu ma} - F_{\mu sp} - F_{\mu st} \qquad \text{eq 1b}$$

If eq 2 is integrated twice the right hand of eq 1b is known. We can then write eq 1b as

$$y'' + c/m \cdot y' + k/m \cdot y = f(t)$$

To avoid the second derivatives we rewrite eq 1b in the form of state space. If eq 1b and the initial conditions is discrethisized we get

$$z'_n + c/m * z_n + k/m * y_n = f_n$$
$$y'_n = z_n$$
$$z_0 = y'_0 = v_0,\ y_0 = 0$$

Make an approximation of the derivatives

$$z'_n = (z_n - z_{n-1})/\Delta T$$
$$z_n = (y_n - y_{n-1})/\Delta T$$

and we, after som rewriting, get equation 3, 4, and 5.

$$z_n = \frac{m\, z_{n-1} - \Delta t(k\, y_{n-1} - c\, x'_n - k\, x_n + F_n)}{m + c\,\Delta t + k\,\Delta t^2} \qquad \text{eq 3}$$

$$y_n = y_{n-1} + z_n \Delta t \qquad \text{eq 4}$$

$$y'_n = z_n \qquad \text{eq 5}$$

$$z_0 = y'_0 = v_0\ ,\quad y_0 = 0$$

From the solution of these equations we get the acceleration, velocity and displacement of the mass.

Results

Special study of the spring

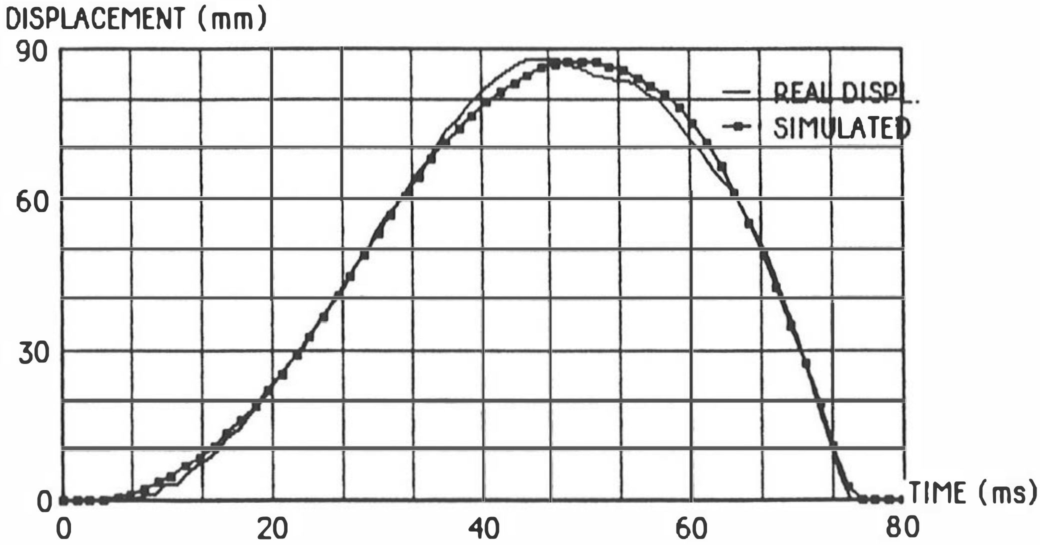
In the beginning of the crash, when the mass starts to move, only the inner turns will be effective and after about 15 ms all turns of the spring will be effective. There is also a small superposition oscillation of the spring during the crash. These fenomenons will not affect the maximum displacement of the mass more than 1% so we neglect them. The extension of the spring caused by its own mass is in the simulation model calculated as putting half of its mass in the end of the spring and then consider it as a light spring.

Comparison between simulated and real displacement
Figure 3 shows a simulated and a real displacement. The following data is measured for the indicator in fig 3.

m_m = 3.25 g
m_{sp} = 4.45 g
k = 25 N/m
c = 0.026 Ns/m

F_0 = 0.44 N
$F_{\mu st}$ = 0.16 N
$F_{\mu ma}$ = 0.0086 N
$F_{\mu sp}$ = 0.0236 N

Fig 3



Analysis of the crash recorder
If the viscous damping is small we can write eq 1 as

$$y'' = -k/m * s - F/m \text{, where } F = F_0 - F_{\mu ma} - F_{\mu sp} - F_{\mu st}$$

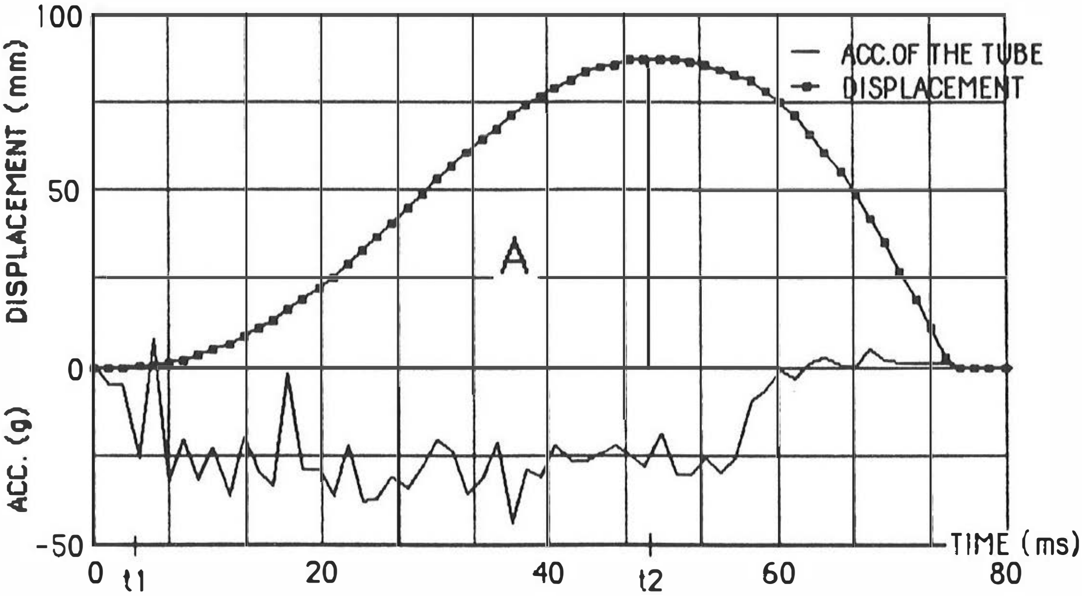
The change of velocity for the mass will then be

$$\Delta V_{mass} = \int_{t_1}^{t_2} y''\, dt = -\int_{t_1}^{t_2} k/m * s\, dt - \int_{t_1}^{t_2} F/m\, dt = -k/m * \int_{t_1}^{t_2} s\, dt - f/m * (t_2 - t_1)$$

where t_2 is the time for the maximum displacement and t_1 the time when the mass starts to move.

Figure 4 shows the area $A = \int_{t_1}^{t_2} s\, dt$.

Fig 4



If we approximate the area A with $C*s_{max}*\Delta t$ we get

$$\Delta V_{mass} \approx -k/m*C*s_{max}*\Delta t - F\Delta t/m \qquad \text{eq 6}$$

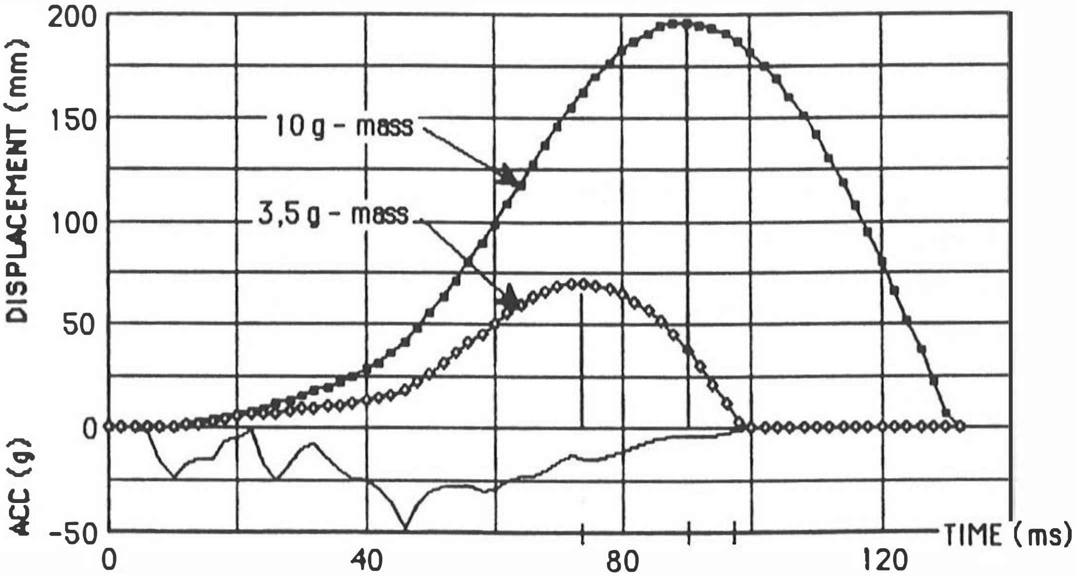
C = constant for the approximation
$\Delta t = t_2 - t_1$
s_{max} = maximum displacement

At the time for the maximum displacement, when the mass turns, the change of velocity for the mass is equal to the one for the tube. It means that we now get information about the acceleration curve of the tube which was the purpose.
If we consider the time for the maximum displacement as unknown, which it in the reality will be, and rewrite eq 6 we get the mean acceleration of the tube, eq 7.

$$a_{mean,tube} = \Delta V_{tube}/\Delta t = \Delta V_{mass}/\Delta t = -k/m*C*s_{max} - F/m \qquad \text{eq 7}$$

One condition that must be fulfilled if the measurement of the indicator is to be relevant is that the time for the maximum displacement is behind or at least in the end of the acceleration curve. If we choose an m_m of 15 g and a k of 25, most of the acceleration curves up to 110 ms will be covered. The parts of the curve which the indicator will not give any information of, is the parts before t_1 and after t_2. It will therefore be a more correct measurement if the mass starts to move early. In figure 5 we can see the displacement with two different masses, one 3.5 g and one 10.0 g.

Fig 5



If we also make an approximation of the time for the maximum displacement we can get the change of velocity.
For a fix m and k the time Δt has a small variation. For $m_m = 15$ g and $k = 25$ the average value of Δt in a series of simulation with 20 acceleration pulses was about 100 ms for frontal impacts.
For angled impacts Δt will be greater, up to 130 ms. With $\Delta t = 100$ ms the average value of C will be 0.435.
Because the crash recorder is to fit in a child restraint the length of the indicator could not exceed 25 cm. That condition will result in a displacement of the mass of maximum 20 cm, which means that m exceed 15 g with a k of 25. A length of the displacement of the mass of 20 cm is, as shown before, enough to make an accurate measurement for the most acceleration curves up to 110 ms.

Accordance between measured and calculated ΔV
The following data shows the accordance between ΔV from calculations based on the simulated output from the crash recorder and real measurements from the tests.

Fig 6

Test		$\Delta V_{measured}$	$\Delta V_{calculated}$
• 50 km/h:	right B-pillar	49.2	36.1
	left B-pillar	"	36.0
	childrestraint front seat, bottom right	"	49.5
	childrestraint front seat, bottom left	"	50.8
	childrestraint rear seat, bottom right	"	47.9
	childrestraint rear seat, bottom left	"	48.4
• 70 km/h:	right B-pillar	69.8	72.0
	left B-pillar	"	69.3
	childrestraint front seat, bottom right	"	92.4
	childrestraint front seat, bottom left	"	90.9
	childrestraint rear seat, bottom right	"	63.9
	childrestraint rear seat, bottom left	"	63.7
• 50 km/h, 30° barrier:	right B-pillar	50.0	49.9
	left B-pillar	"	40.2
	childrestraint rear seat, bottom right	"	51.8
	childrestraint rear seat, bottom left	"	50.0

Comparison between acceleration curves for the car and the child restraints
In figure 7, 8 and 9 we can see the differences between the acceleration curve for the car and for rearward facing child restraints placed both in the front and the rear seat. The curve for the child restraints are smoother in the beginning and the shape is more triangular than the curve for the car.

Fig 7

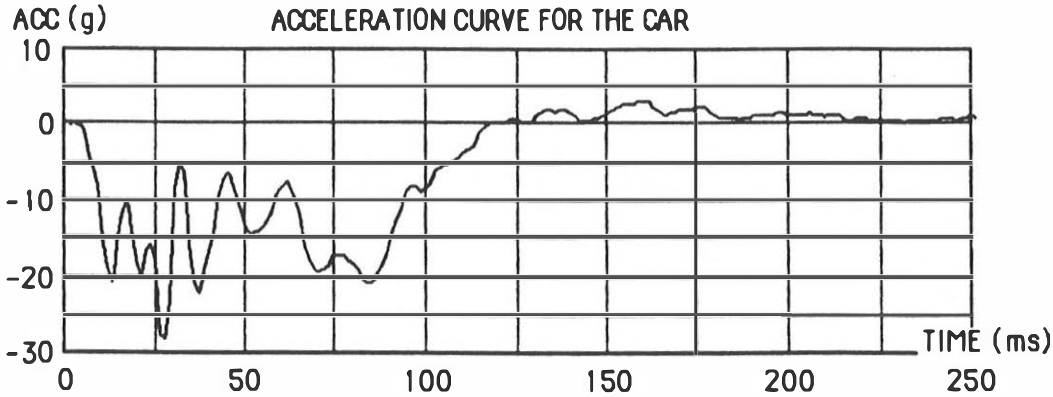


Fig 8

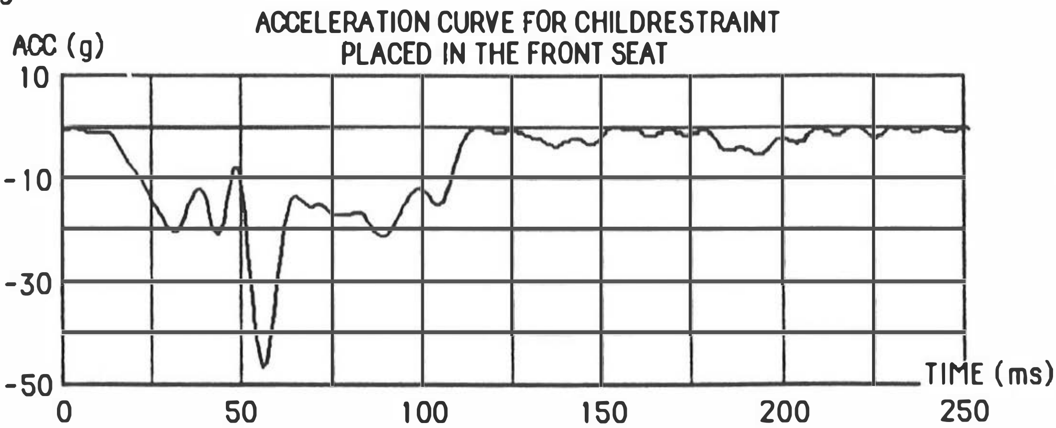
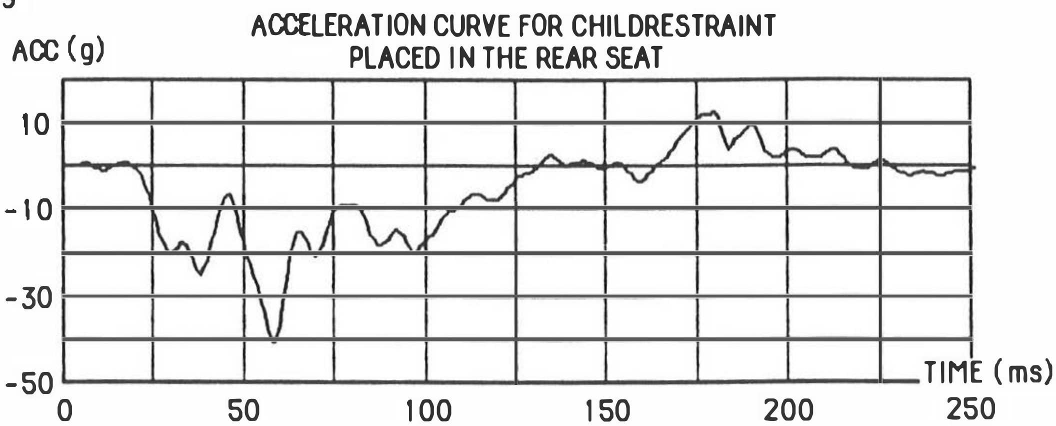


Fig 9



Discussion

In order to classify the severity of a specific accident and according to that the risk for an occupant of being injured due to that specific severity it is necessary to have some measurement related to the crash behavior of the car. It could be the change of velocity or some measurement of the acceleration of the car. (1, 2).

By measurements of the car and by considering the circumstances of the accident it is possible to get an idea about the change of velocity and the time for the main part of the acceleration.

With a crash recorder of a mass-spring system it is possible to calculate the mean acceleration with an accuracy of 5% which probably is a great improvement compared to calculation based on manual measurements of deformations of the car. Combining the results from the crash recorder with the manual measurements of the impact of the car it is possible to calculate an approximate value of the change of velocity with almost the same accuracy as for the mean acceleration.

In the calculations of the change of velocity two approximations are made. One is about the area under the displacement curve for the mass in order to calculate the mean acceleration and the other is about the time for the maximum displacement in order to calculate the change of velocity. These approximations will reduce the accuracy with maximum 5% provided that some acceleration curves are sorted out by studies of the damaged car and circumstances in the crash.

There is also one detail on the indicator which will reduce its accuracy. The string has a frictional drag which in retrospect is hard to define. The frictional drags has to be constant and easy to define if the indicator is to give an accurate measurement.

One factor which will influence the maximum displacement, except all the parameters as m, k, $F_{\mu st}$ etc shown above, is the shape of the acceleration curve. If the main part of the change of velocity is in the beginning of the curve the crash recorder will give an incorrect measurement. The mass will reach its maximum displacement and turn in the middle part of the acceleration curve. The best situation is to have a smooth beginning of the acceleration curve and the main part of the change of velocity located in the end of it. If the indicator is mounted in a child restraint, which will make the acceleration curve smoother (see fig 7, 8 and 9), the output from the crash recorder will be more correct. In a real collision it is important to look at the collision type and the circumstances of the accident and then separate the collisions that may give an incorrect output of the indicator.

In fig 6 there is some differences between calculated values of ΔV and the real measurements. In the 50 km/h test there is in the acceleration curves for the B-pillars a great change of velocity in the beginning of the pulse that results in an incorrect approximation of the area under the displacement curve. The front seat mounted child restraint in the 70 km/h test was hit by the instrumental panel and therefore the change of velocity which the crash recorder measures is to high. The difference for one of the measurements in the angled crash is also due to the shape of the pulse. It should be noted that this is the accordance between calculations based on the simulated output from the crash between calculations based on the simulated output from the crash recorder and not from the crash recorders mounted in the car. As the crash recorder at this stage is constructed there is to much variation of the frictional drag from the string. This leads to a higher random error than necessary.

The crash recorder measures until the time for the maximum displacement of the mass. The rebound of a child restraint placed in the rear seat (see fig 9) will occur after the maximum displacement and therefore it will not contribute to the measurement of the mean acceleration. Because of the fact that we measure the mean acceleration in order to calculate the change of velocity it is not so critical if some small parts in the end of the acceleration curve will be passed over. In most cases it does not affect the measurement more than a few percent.

The details of the indicator which have to be improved is the determination of the maximum displacement and also to include determination of the time for the maximum displacement. The first step to improve the measurement will be to replace the string with some kind of device which has a constant and well defined frictional drag, for example if the mass scribed its location on the inside of the tube. Another way to eliminate the frictional drag caused by the string is to attach a small magnet on the mass which in a crash will be pulled out on a magnetic tape which then will be magnetized till the maximum displacement.

If the time for the maximum displacement could be measured we would not have to make the second approximation in order to calculate the change of velocity. The aim is to in some way measure the displacement curve for the mass during the crash. There are several simple ways to achieve such kind of device, for example if there is a constant speed rotating mass-spring system inside the tube. The displacement of the mass could then be drawn on the inside of the tube during the crash. The same result will be achieved if the tube could be rotating. In these cases no approximation is necessary and the accuracy of the measurement will almost only depend on the precision of the manufactured indicator.

References

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