OBLIQUE IMPACTS - A PARAMETRIC STUDY IN CRASH HELMETS

by

B. Aldman, B. Lundell and L. Thorngren

Department of Traffic Safety, Chalmers University of Technology, Gothenburg, Sweden

Background.

In a previous paper (Aldman et al 1976) a method was described where oblique impacts of a helmeted head on surfaces with different characteristics can be simulated. This method utilizes the head and neck of an anthropometric test dummy in a free fall against a rotating disc with means to retain the impact surface material. Figure 1. The hight of the free fall and the number of revolutions per minute of the disc determine the velocity vector of the appulse. The simulation of various head attitudes can be achieved by using a number of different mounting brackets. Since the device was designed for the study of head impacts, efforts have been made to minimize any unrealistic influence from the surrounding structures and tests have been carried out both with a very firm support for the head, a rubber neck, and with the head falling freely without any connection at the neck. In a preceding paper a validation of this method against drop tests with a complete dummy is described.

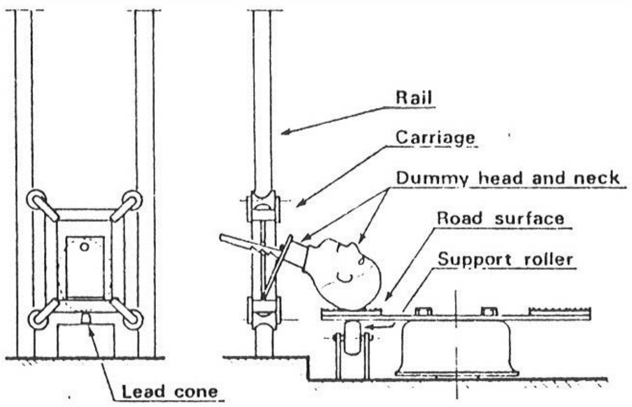

Figure 1. Test device for oblique impacts of crash helmets.

The aim of this paper is to report results from a parametric study of the dynamic behaviour of a helmeted head in oblique impacts to rigid surfaces. The impact situations, and particularly the attitude of the head at impact, have been chosen with the purpose to enable the study of a certain parameter rather than to simulate realisticly a certain accident situation. It should be pointed out, however, that although some of the impact situations reported may seem extreme and may rarely occur in accidents, it is the opinion of the authors that none of the situations is completely unrealistic.

Since, in this method, a head falls against a rotating disc it is easiest to think of this as a simulation of a two-wheeled vehicle rider impacting the ground after having been air-borne for some distance. Terms like vertical velocity, horizontal velocity etc are used in this paper as they refer to the test situation. However, since both vehicles in a collision are usually moving in different directions, a head impact to another vehicle is normally also an oblique impact. This type of collision can be simulated in the same way, one only has to imagine that the reference system has been turned 90 degrees so that one of the velocity components in the test situations becomes vertical.

Instrumentation.

The linear and angular accelerations of the head may be determined using various combinations of e.g. rate gyros, angular accelerometers and linear accelerometers. Two methods have been discussed in a number of papers (King et al 1974, Padgaonkar et al 1975, Johnson et al 1977, Stalnaker et al 1977). Both utilize linear accelerometers, one in a 6-accelerometer arrangement and the other in a 9-accelerometer arrangement.

The 6-accelerometer method has the obvious advantage of using fewer accelerometers. However, the equations for the angular accelerations include not only the linear accelerations but also the angular velocities. This makes numerical integration procedures necessary which reduces the accuracy of the results. Furthermore, as shown by Padgaonkar et al 1975, the integration is unstable and thus will "blow up" after some time.

Due to the higher accuracy and the lack of stability problems of the 9-accelerometer method it is recommended in most papers dealing with the two methods. However, as pointed out by Stalnaker et al 1977, the simpler 6-accelerometer method can be advantageous in many cases, where the time of interest is short as compared to the time when the problems of accuracy and stability occur in the integrations. This is, in our opinion, the case for the type of situation that we have studied, where the impact sequence has a total duration of approximately 10 milliseconds and peak accelerations occur at approximately 5 milliseconds from the beginning. After such a short time the angular velocity is still so low that it can be approximated to zero. If this is done, that is to say that no integration of the angular velocity is performed, the resulting error in the peak resultant acceleration will never be more than approximately 1% and the error in the resultant angular acceleration at the end of the impact sequence will be within a few hundred rad/s^2. As these errors are small in comparison with other errors in this kind of simulation, a modified 6-accelerometer method was used and angular accelerations calculated without the integration procedure for angular velocity.

The instrumentation used consisted of two tri-axial linear accelerometers and one angular accelerometer. In this way one angular acceleration component $\dot{R}_y$ could be measured directly while the other two, $\dot{R}_x$ and $\dot{R}_z$ had to be calculated from the linear accelerations. Figure 2. The instrumentation also included strain gages on the proximal end of the rubber neck, so that the moments at this point could be measured. A linear accelerometer was also used to measure the vertical deceleration of the carriage.

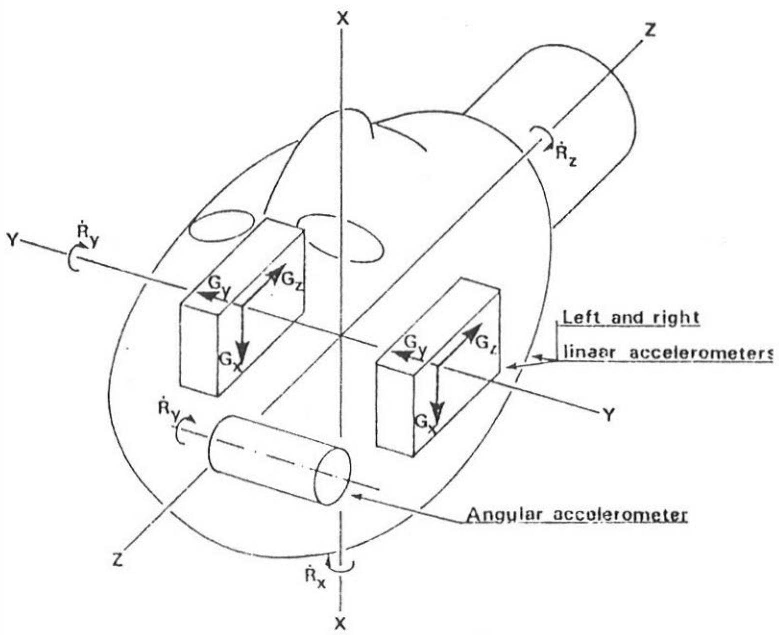

Figure 2. Instrumentation of the dummy head.

Results and discussion.

The results from these investigations are presented in three major groups. In the first group the results relate to the consequences of using a rubber neck to attach the head to the guided carriage in the main test series. The second group of results apply to the influence from the parameters: vertical velocity, horizontal velocity, head attitude, impact surface and helmet shell material. In the third group results from calculations of angular velocities are presented together with peak values for linear and angular accelerations in relation to published tolerance levels.

For the main test series, and unless otherwise stated, the following conditions apply. The dummy head was mounted with its sagittal plane vertical, the face turned up and the neck inclining 24 degrees downwards from the horizontal plane. The horizontal velocity was 8.3 m/s with the road surface perpendicular to the sagittal plane of the head. The vertical velocity was 5.2 m/s (falling hight 1.4 m). The impact surface was a 20 mm wood particle board secured to the rotating disc and covered by grinding cloth, Naxos CKRG 20.The helmet was a jet type, open face helmet with a liner of expanded polystyrene and a polycarbonate shell. The results concern only the impact sequence.

In order to demonstrate the influence of the rubber neck on the resultant angular acceleration of the head, five tests were made with the head disconnected from the carriage and with the rubber neck removed. Otherwise the conditions at impact were the same as in the main test series. In figure 3 the mean curve of the resultant angular acceleration from these five test is presented together with the mean curve from five standard test, where the rubber neck was connected to the head and to the carriage, and with the mean curve from two of the tests with a complete dummy dropped under similar conditions on an asphalt concrete surface.

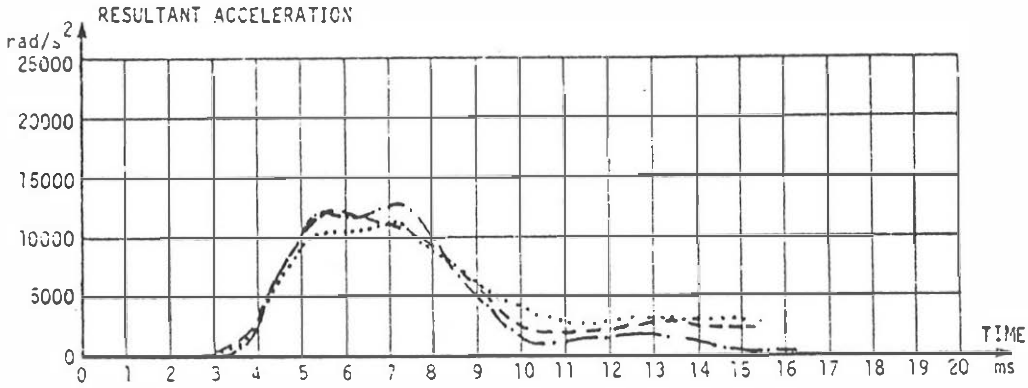

Figure 3. Comparison between three different test series with the same simulated impact attitude
- - - - - Head and neck mounted on the carriage. Mean result from five tests
- . - . - Free falling head. Mean result from five tests
. . . . . Complete anthropometric dummy. Mean result from two tests.

The linear accelerations from these tests are not presented but demonstrate a similar pattern. The results indicate that a possible influence from the rubber neck during impact falls within the normal scatter of the results from identical tests (cp. fig. 4). This similarity between the angular acceleration curves, with and without the rubber neck, applies only to the standard test situation used in the main test series, where the horizontal velocity vector is perpendicular to the sagittal plane and the rubber neck subjected to torsion. If the horizontal velocity vector is parallel to the sagittal plane the neck is either compressed or extended which has a more pronounced influence on the acceleration of the head (cp. fig. 9 and 10). This is one of the reasons for chosing the head attitude used in the main test series.

Before going into the different parameters studied, it is of interest to estimate the scatter between identically performed tests. The results from five such tests with the standard type of helmet are shown in fig. (4) and summarized together with results from five tests with another helmet in table 1 below.

Helmet designation	Helmet shell material	Peak linear acceleration g´s	Peak angular acceleration			No of tests
			Mean rad/s^2	min-max rad/s^2	stand.dev. rad/s^2	
B	Polycarbonate	118-140	12500	11400-13000	690	5
D	ABS	138-162	13800	13200-14700	540	5

Table 1.

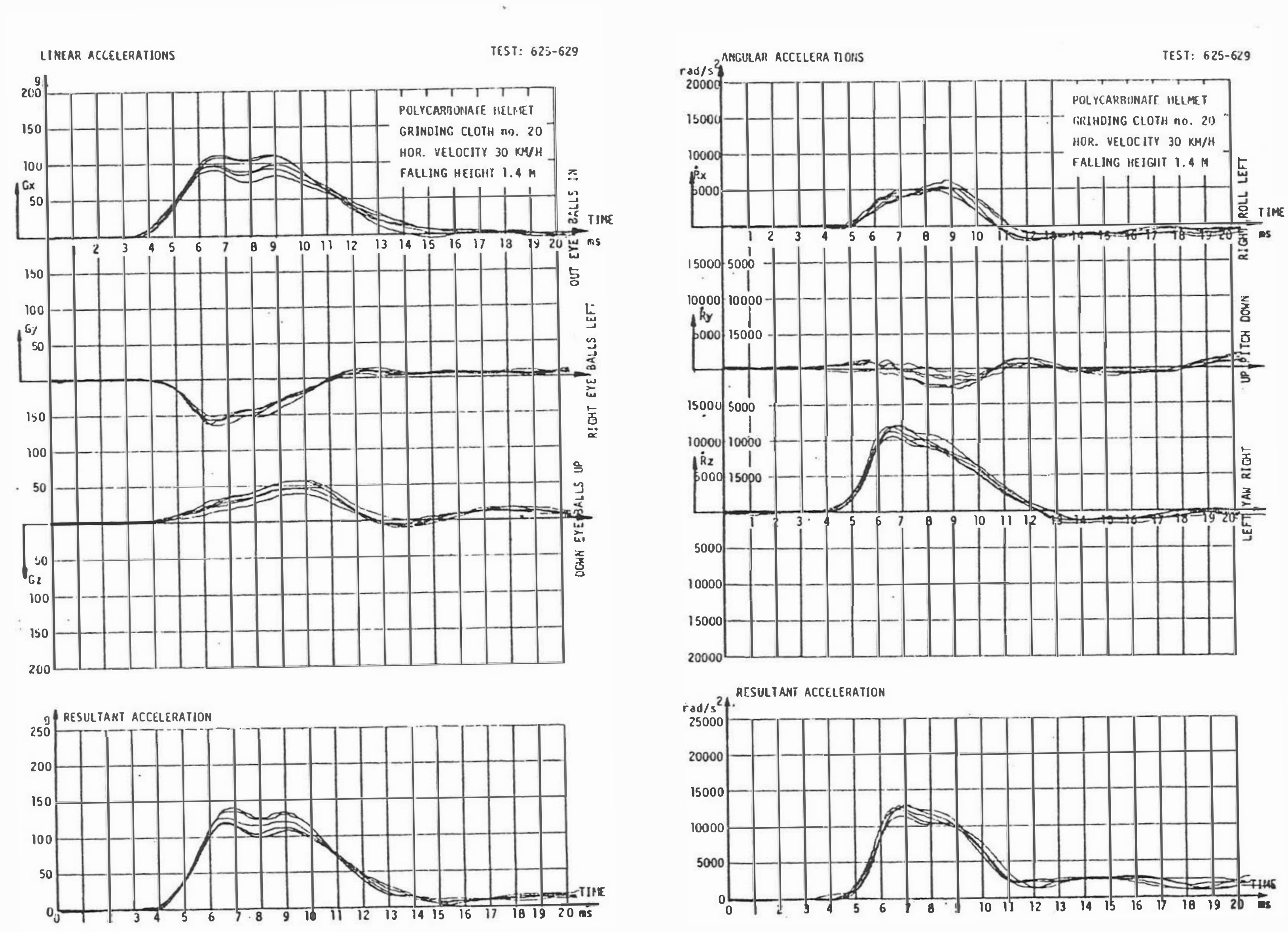

Figure 4. Linear and angular accelerations recorded in five identically performed tests under standard conditions.

Two important parameters are helmet type and impact surface. A number of tests were performed with five different makes of helmets and using eight different types of surface materials. The helmets were all of the jet type, open face helmets with a liner of expanded polystyrene. The thickness of the liner and of the comfort padding varied slightly between the types and there were three different types of shell materials represented. The impact surfaces used were of four main categories.

- a 20 mm thick layer of asphalt concrete Ab8t (a type common in cities) placed on top of the rotating steel disc,
- a 20 mm thick wood particle board secured on the rotating steel disc,
- grinding material (Naxos CKRG 20 or Norton Closecote Silicon Carbide No 80) glued on top of the wood particle board,
- stones of different shapes and sizes glued on top of the wood particle board.

The asphalt concrete surface was used only in a few tests due to its low strength when exposed to the centrifugal forces of the rotating disc.

The results of all these tests are summarized in tables 2 and 3 below.

Surface no	Surface typ	Peak linear acceleration g's	Peak angular acceleration mean rad/s²	Peak angular acceleration min-max rad/s²	Peak angular acceleration stand.dev. rad/s²	No of helmet types	Fig no
1	Asphalt concrete	130-165	11500	10300-12500	1000	4	
2	4 mm angular stones	140-180	10500	7900-15000	2800	5	
3	12 mm angular stones	115-180	12700	10500-15400	2000	5	5
4	12 mm round stones	105-160	8400	5800-11200	2200	4	
5	Surface no 4 + oil	115-165	7300	4800-9100	1900	5	
6	Wood particle board	145-165	9000	7800-10300	1100	5	
7	Grinding paper no 80	105-135	13700	11800-15000	1400	4	
8	Grinding cloth no 20	135-175	14400	13500-15000	600	5	6

Table 2.

Helmet designation	Helmet shell type	Peak linear acceleration g´s	Peak angular acceleration mean rad/s²	min-max rad/s²	stand.dev. rad/s²	No of surface types	Fig no
A	Fiberglass	115-150	10100	6300-14000	3000	8	
B	Polycarbonate	125-180	10600	4800-15000	3800	8	7
C	Polycarbonate	105-150	10300	5400-13100	2400	8	
D	ABS	135-165	11300	7700-14600	2300	8	
E	ABS	150-180	12500	9200-15400	2900	5	

Table 3.

Figure 5 shows the resultant angular acceleration from tests with five different helmets impacting surface No 3, which had 12 mm angular stones glued to the wood particle board. The configuration of these curves is about the same, but the peak values differ from 10500 to 15400 rad/s^2 with a mean of 12700 rad/s^2.

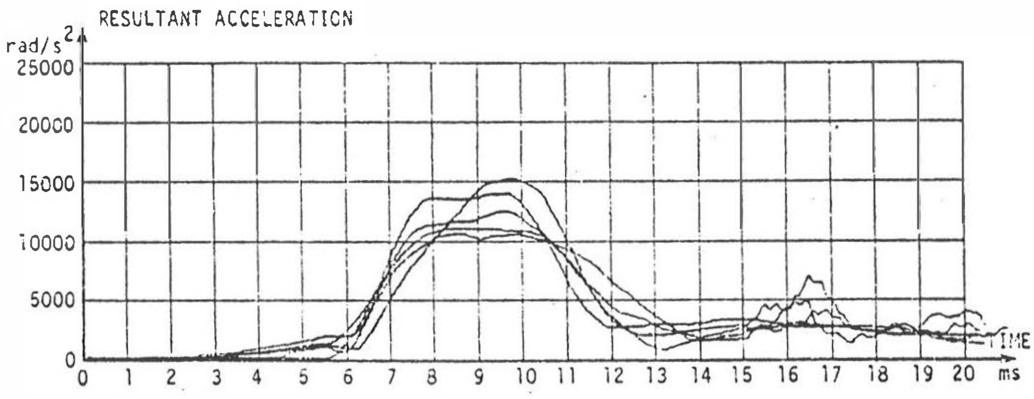

Figure 5. Surface no 3 (12 mm angular stones) tested with five different helmets.

Figure 6 shows the resultant angular accelerations from tests with five different helmets impacting surface No 8, which had Grinding Cloth No 20 glued to the wood particle board. The differences between the individual curves are much less than in figure 5, but the mean of the peak values is higher, it is in fact 14400 rad/s^2.

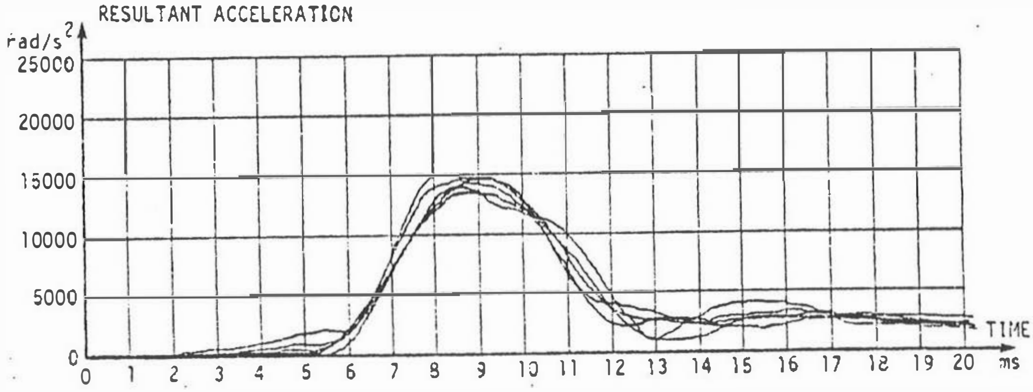

Figure 6. Surface no 8 (grinding cloth no 20) tested with five different helmets.

In figure 7 is shown the resultant angular accelerations from impacts of the same make of helmet, designated as helmet B in table 3, into the eight different road surfaces.

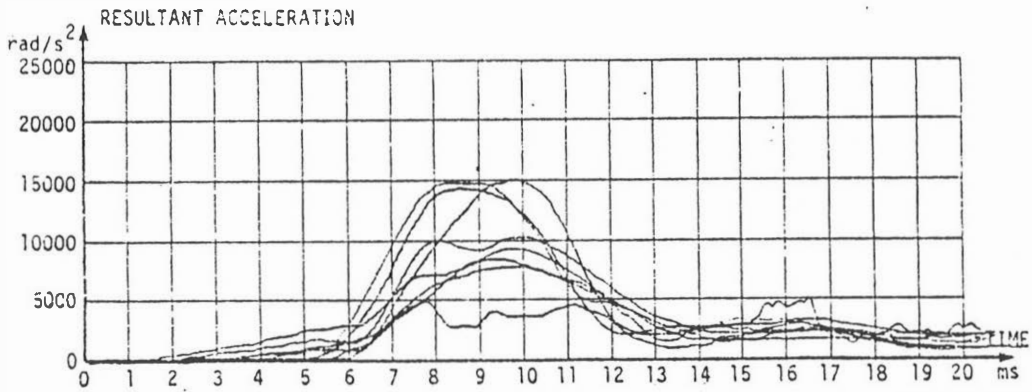

Figure 7. Helmet type B (polycarbonate shell) tested on 8 different surfaces.

It is obvious that the characteristics of the road surface have great influence on the resultant angular acceleration of an impacting helmeted head and that road surface No 8 gives high but not unrealistic peak values.

The linear deceleration graphs are not shown here because there is no great difference neither between the different helmets nor between the different surfaces. HIC values calculated on the linear resultant deceleration was in most cases below 1000 and in a few tests close to 1300.

Another interesting parameter is head attitude at impact. In the previously discussed tests the head y-axis was horizontal and the horizontal velocity component was perpendicular to the head z-axis. This could for instance simulate a body moving sideways with his face upwards. Figure 8 shows the results from tests where the horizontal velocity component was still perpendicular to the head z-axis but the direction of the head y-axis was altered. Each curve is the mean of two or more tests.

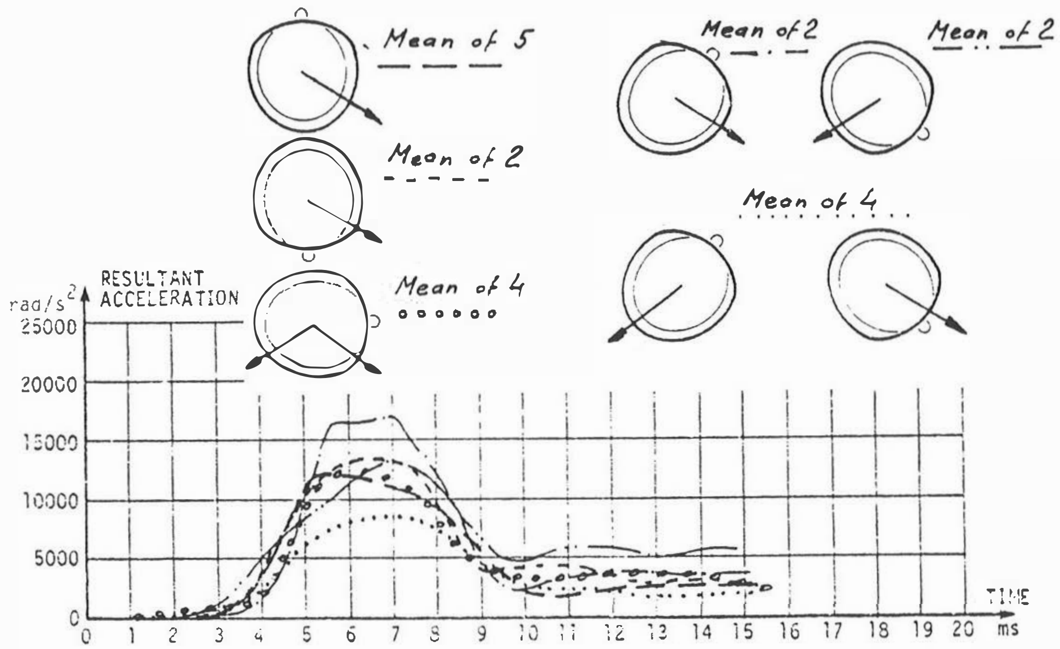

Figure 8. Results from tests with various head attitudes, the arrow indicates the velocity vector.

The differences in resultant angular acceleration when the head attitude is altered the way it was in these tests might be explained by the fact that the helmets have an oval cross-section when viewed from the top.

Another interesting head attitude is the situation where the horizontal velocity component is parallel to the sagittal plane simulating for instance a body moving in the longitudinal direction at ground impact. Figure 9 shows the results in a simulated head-frist situation. The dashed curve represents the mean of two tests with head and rubber neck mounted on the carriage and the dash-and-pointed curve is from a test with complete dummy, both in the face--up position. The full line represents the mean of two tests with head and rubber neck mounted on the carriage in the face-down position.

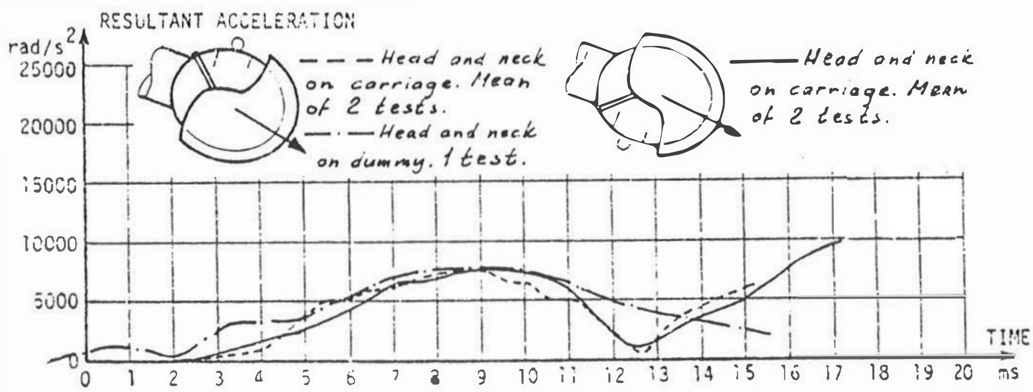

Figure 9. Results from simulated impacts with the head as leading part.

The configuration of these curves and the peak values are quite similar in these tests.

Figure 10 shows the results from a simulated feet-first ground impact situation. The various curves represent the same number and type of tests as in figure 9.

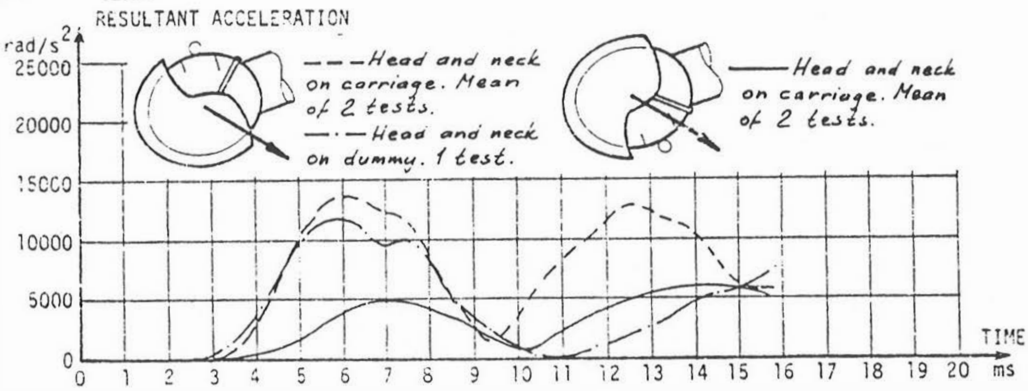

Figure 10. Results from simulated impacts with the feet as leading part.

The two curves from the face-up situation are quite similar. The reason for the difference between these two curves and the one from the face-down situation is probably the fact that the helmets slide more easily on the head in the latter type of impact and a quite noticable rotation of the helmets relative to the head was seen in the high-speed films from these tests.

The results reported here have, so far, been from tests where the vertical and the horizontal velocity components were equal. The only exception being some test with a complete dummy. Two other test series were performed where the two velocity components were different. In one, both components were altered in such a way that the amplitude of the resultant velocity vector was held constant at 5.2 m/s. In the other, the vertical velocity was held constant at 5.2 m/s and the horizontal component was 8.3, 12,5 and 16.7 m/s (30, 45 and 60 km/h). The velocity vectors and the peak linear and angular accelerations from these two series are shown in figure 11.

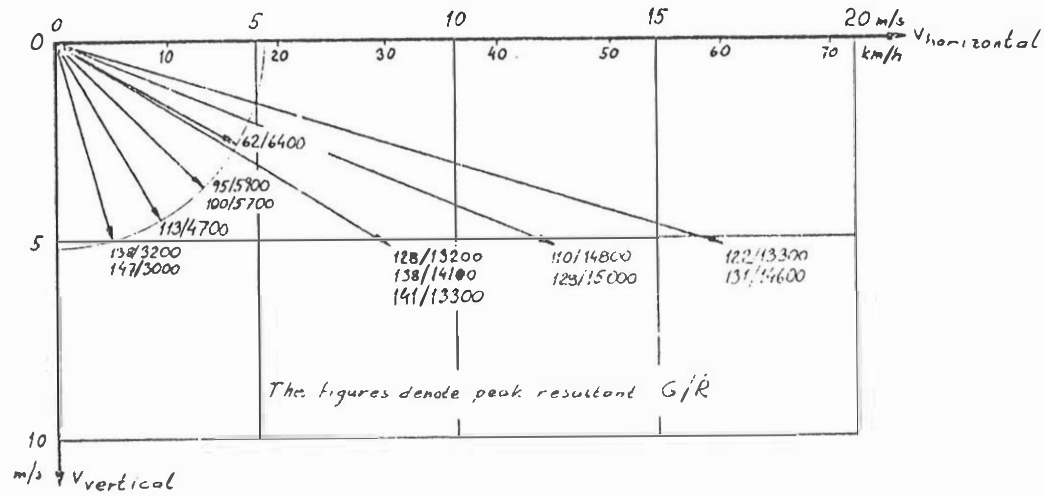

Figure 11. Tests with different vertical and horizontal velocities.

Although the whole spectrum of linear and angular velocity combinations was not covered in these tests, it seems likely that the peak linear acceleration is mainly a function of the vertical velocity. For the three horizontal velocities 8.3, 12.5 and 16.7 m/s the peak angular acceleration is fairly constant. For velocities lower than these the angular acceleration varies in a more complex way. This will be discussed in a later section.

A few tests have been made with full-face, integral helmets. Some results from these tests are summarized in table 4. In all the tests the vertical velocity was 5.2 m/s but the horizontal velocity varied between 8.3 and 16.7 m/s. The head attitudes shown in figure 8 were used in these experiments.

Helmed designation	Helmet shell material	Peak linear acceleration g´s	Peak angular acceleration mean rad/s²	min-max rad/s²	stand.dev. rad/s²	No of tests
F	Polycarbonate	165	15750	1400-17500	-	2
G	Polycarbonate	125	10300	-	-	1
H	Fiberglass	110-145	13400	11000-16000	2400	6
J	Fiberglass	75-135	8500	6000-12500	2300	7

Table 4. Some results from tests with full-face, integrated helmets.

According to Ommaya and Hirsch 1971 the angular acceleration tolerance level against cerebral concussion is 1800 rad/s² and according to Löwenhielm 1974-75 the corresponding level against bridging vein rupture and gliding contusion is 4500 rad/s². These authors consider the figures valid only if the resulting change in angular velocity also exceeds a limiting value somewhere between 50 and 70 rad/s². In figure 12 the peak angular accelerations from the same tests as in figure 11 are shown together with the tolerance levels.

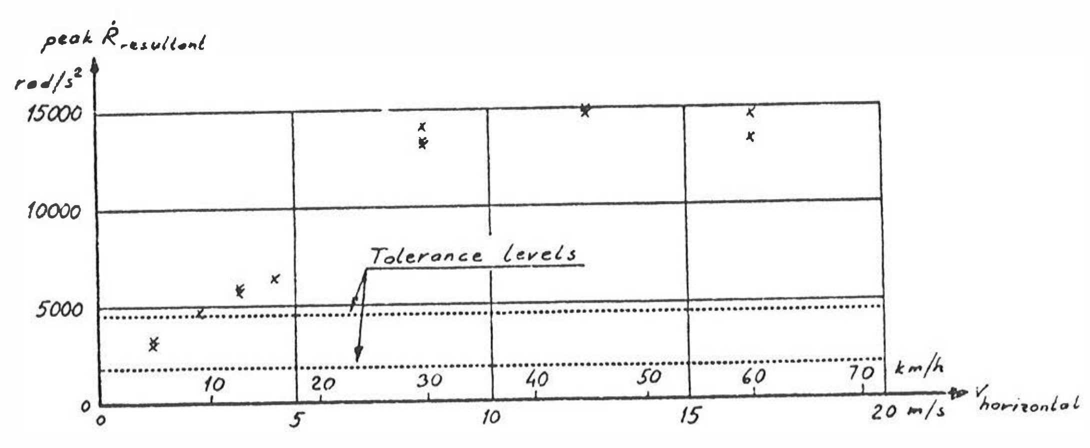

Figure 12. Peak angular accelerations as a function of horizontal velocity.

The calculated changes in angular velocity from these tests are plotted in figure 13 and the tolerance levels indicated.

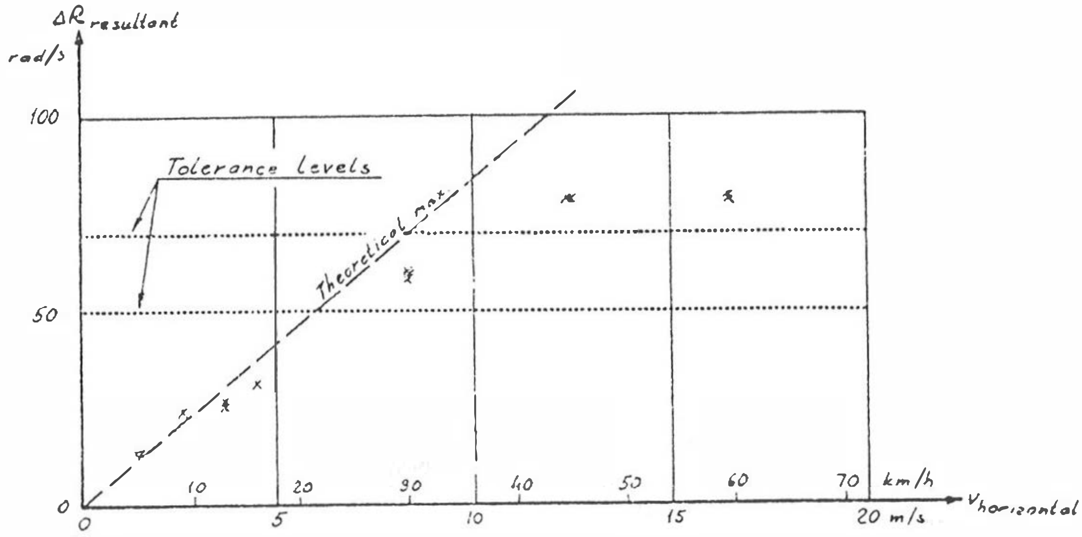

Figure 13. Total change in angular velocity as a function of horizontal velocity.

In this figure a straight line indicates the angular velocity which corresponds to a theoretical situation where a spherical helmet rolls without slip on the impact surface and its center moves at the corresponding velocity indicated on the x-axis. In reality the motion is more complex and angular velocities calculated on the resultant can exceed the values indicated by this line. At low horizontal velocities there is an almost linear relationship between the horizontal velocity and the angular acceleration. This is the case also for the angular velocity change. At higher horizontal velocities both angular acceleration and angular velocity change remain at a fairly constant level. In these tests the tolerance levels for angular acceleration as well as for angular velocity change were exceeded in the tests performed at higher horizontal velocities.

Conclusions.

- For tests performed under standardized conditions the method used in this investigation gave similar results and a reasonably low scatter in peak accelerations. Therefore the method can be considered to be suitable for this kind of studies.
- The attidude of the head had some influence on the accelerations recorded at impact. Relative movements between helmet and head were small in most situations simulated but a possible influence from such movements should be considered when the results are interpreted.
- The characteristics of the impacted surface influence the results very much and also very smooth surfaces were found to cause high angular accelerations.
- In oblique impacts both velocity components influence the results. Since head impacts to the other vehicle in a collision are usually oblique

both velocity components can be expected to attain high values in real accidents.

- At higher velocities, published tolerance levels for both angular acceleration and angular velocity were exceeded in the tests. It seems probable that similar mechanisms could be the cause of some of the injuries encountered in real accidents.
- The different characteristics of the shells used in these tests had only minor influence on the angular accelerations caused by the oblique impacts. In efforts to reduce peak angular accelerations consideration should also be given to the liner characteristics since a reduction of peak linear acceleration will also result in a lowering of the peak angular acceleration.
- The results of this investigation indicate that it would be desirable if the human tolerance to angular acceleration and angular velocity change could be better established under different impact conditions. It would also be of interest if the connection between the tolerance levels for linear and angular accelerations could be clarified since the peaks occur at the same time.

References.

ALDMAN,B., LUNDELL,B., THORNGREN,L. (1976): Non-Perpendicular Impacts - An Experimental Study on Crash Helmets. Proceedings of the Meeting on Biomechanics of Injury to Pedestrians, Cyclists and Motorcyclists. Amsterdam 7-8 September 1976. pp 322-331

KING,A.I., PADGAONKAR,A.J., KRIEGER,K.W. (1974): Measurement of Angular Acceleration of a Rigid Body Using Linear Accelerometers. The Second Meeting on Human Subjects for Biomechanical Research. December 6, 1974.

PADGAONKAR,A.J., KRIEGER,K.W., KING,A.I. (1975): Measurement of Angular Acceleration of a Rigid Body Using Linear Accelerometers. J. of Appl. Mech. September 1975. pp 552-556

JOHNSON,A.K., HU,A.S. (1977): Review of Head Rotational Measurements During Biomechanical Impact Tests. NHTSA Technical Report, DOT HS-802,568, August 1977

STALNAKER,R.L., ALEM,N.M., BENSON,J.B. (1977): Validation Studies for Head Impact Injury Model. NHTSA Technical Report. DOT HS-802 566. September 1977

OMMAYA,A.K., HIRSCH,A.E. (1971): Tolerances for Cerebral Concussion from Head Impact and Whiplash in Primates. Journal of Biomechanics 4, 13, 1971

LÖWENHIELM,P. (1974): Strain Tolerance of the Vv Cerebri sup.(Bridging Veins) Calculated from Head-on Collision Tests with Cadavers. Z. Rechtsmedizin 75, 1974, pp 131-144

LÖWENHIELM,P.(1975): Mathematical Simulation of Gliding Contusions. J. Biomechanics, 1975,Vol.8, pp 351-356.