HEAD BIOMECHANICS:
FROM THE FINITE ELEMENT MODEL TO THE PHYSICAL MODEL

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ABSTRACT

The objective of this work is to characterize the human head dynamic response under shock conditions by a new 3D finite element model and to transfer the results to a physical model intended for "measuring" the shock severity.

The proposed3D FEM distinguishes the different anatomical features of the cerebral matter. Model validation is based on it's theoretical modal analysis compared to the in vivo mechanical impedance recordings of the head. Modal analysis of the model shows three vibration modes. The mode shapes are illustrated by brain rotations around the Z1, Y1-Y'1 and X1 axis respectively making an angle of $\pi/8$ rad with the Z, Y, and X reference axis.

The new proposed physical head model thus has an internal mass modeling the cerebral mass. The modelising of the mechanical liaisons between the brain and skull was achieved by visco-elastic liaisons. The adjustable elastic component permits 3 degrees of freedom relative to the brain-skull movement (two X, Y translations and the rotation around Z). The resonance frequencies of these three degrees of freedom were fixed by the theoretical modal analysis of the 3D finite element model

This new head models are especially suitable for distinguishing the risk of focal lesion or sub-dural haematoma from diffuse axonal injury risks.

TO PROVIDE OPTIMUM PROTECTION of the human head when subjected to a shock requires a thorough knowledge of the "object to be protected". Biomechanic investigations of shocks applied to the head, carried out at the Biomechanical Systems Laboratory of Strasbourg University (URA CNRS 854), have provided a better understanding of the in vivo dynamic behaviour of the cephalic segment and thus the lesion mechanisms involved in cases of cranio-cerebral traumatism (Willinger 1991).

Optimizing human head protection depends on the evaluation and preparation of a product or device aimed at protecting the human head, such as a crash helmet. It also involves evaluating and then improving existing products or devices which represent a danger to the human head, such as the dashboard. The work presented here is a stage in this direction, since it concerns applying fundamental research results to experimental investigations. In spite of the appearance of more and more sophisticated theoretical models, shock tests will still have an important role, in view of the complexity of certain impacted structures and the need for certification test procedures.

The scientific community specialized in the field of head biomechanics has agreed to consider the head as a non-rigid structure made up of several components (Hodgson 1967, Stalnaker 1971, Viano 1989, Thibault 1990, Willinger 1991). However, despite this consensus, both European and North American standards recommend, for cephalic shocks severity tests, a dummy head which is nothing more than a rigid body on which it is also recommended to record the centre of gravity acceleration. It is this temporal acceleration function which is at the basis of the famous HIC (Head Injury Criteria) calculation. The criterion of HIC are due to considering the head only as a rigid body and its simple kinematic analysis (Stalnaker 1971, Viano 1989, Thibault 1990, Dimasi 1991).

Even though the HIC is representative of a certain shock severity level, and therefore a certain cerebral lesion risk, it is clearly not capable of distinguishing between the different possible lesion mechanisms. Knowing the sensitivity of the nerve cells to shear stresses and the importance of the brain-skull relative displacement phenomena, one can appreciate how difficult it is to assess these magnitudes just by the acceleration of a unique body.

The objective of our study is to improve the experimental and theoretical evaluation methods of the severity of cephalic shocks by taking into account various lesion mechanisms and integrating the recording of certain intracranial mechanical parameters in real shock situations.The subject of this study concerns an alternative to the existing test dummy, by replacing this human head substitute by a structure made up of two masses, whose 3 D dynamic characteristic comes close to those of the head.

In this study we show how it is possible, by recording the in vivo mechanical impedance of the head, to construct an original 3D FE model whose modal analysis gives results which can be directly used for constructing a new dummy head. This study focuses on taking into account, in the theoretical and physical models, the head's natural frequency recorded at around 100 Hz. This modal behaviour, established by Willinger in 1990 and consistent with other authors, (Hodgson 1967, Slattenschek 1968, Ruan 1992, Troseille 1992) is of fundamental importance in lesion mechanisms caused by shock. It especially modulates the importance of the relative brain-skull movement and thus conditions the appearance of subdural haematoma and focal contusions or diffuse axonal injuries. This analysis which is intended for modeling the head's first vibration modes does not therefore take account of lesion mechanisms related to skull deformations which only occur in very short duration shock situations rarely encountered in automobile crashes. The first section presents and describes the method proposed in this approach. The second section presents the finite element model developed in the laboratory and its modal analysis. In the third section a physical model of the head and its modal and temporal analysis is proposed. In the conclusions, the limits and benefits of such an approach are discussed.

METHOD

GENERAL ASPECT - The methods applied use to a large extent the structure's theoretical and experimental modal analysis. In this approach, the modal parameters (natural frequency, damping and mode shapes) comprise the objective parameters in the validation process. The linear mathematical model validated in accordance with this principle and subjected to external forces shows, in the temporal area, deformations conforming to the calculated mode shapes or to a linear combination of them. In the case of non-linear saturation behaviour as seems to be the case for the head, the non-linearities only show up as of a certain stress level, when the material is very deformed or when the brain comes in contact with the skull. Under moderate excitation, the linear hypothesis is satisfied and the mode shapes illustrate the initialisation of structure movements and deformations since these are the deformations obtained for a minimum energy. By nature, these models will be well adapted for studying lesion mechanisms and not for studying tolerance limits under shock conditions.

The approach followed in this study realizes the coupling between the in vivo vibratory analysis of the head, with the preparation and study of a 3 D finite element model, then the construction of a prototype dummy head. In fact the brain decoupling phenomena at 100 Hz observed in vivo in the sagital plane (Willinger 1990), was reproduced on a new 3 D finite element model. The theoretical modal analysis of this 3D FEM has itself shown that this decoupling phenomena at 100 Hz also occurs in the frontal plane with a rotation around an axis close to the anteroposterior, as well as in the horizontal plane with a rotation this time around a virtually vertical axis. The end of this reasoning therefore consists of producing a prototype dummy head able to reproduce the relative brain skull movement in both frontal and lateral shock situations as well as the cerebral mass rotation in the case when the head is subjected to a sudden rotation around the vertical axis.

EXPERIMENTAL METHOD - The same method was used for the vibratory analysis of the human head and that of the prototype dummy head.

From the experimental viewpoint, the method depends on studying the transfer function between the exciting force and the structure's response. This transfer function or mechanical signature, can be defined in terms of apparent mass, mechanical impedance or receptance, provided that the response recorded is respectively acceleration, velocity or displacement. The punctual mechanical impedance is then the ratio between the force and displacement velocity of the structure point considered, expressed in the frequency area by the Fourrier transform (Harris 1988).

In the general case of a continuous deformable structure, the global description requires studying a large number of transfer functions between the impacted point and various points of the structure. For a given natural frequency, the amplitude and phase of these transfer functions make it possible to construct the corresponding mode shape.

For a given degree of freedom, the structure can be characterized by its behaviour according to a particular direction. In this case, a single transfer function (or a single mechanical impedance) is sufficient to inform us about the natural frequencies, damping and de-coupled modal masses for this direction. In practice, it is a matter of applying a moderate intensity impulse to the frontal area of the biological or physical head by means of a hammer fitted with a force tranducer. The response is recorded by a piezo-electric accelerometer placed near the impact point. These two signals are expressed in the frequency area by their Fourrier transform. The punctual mechanical impedance is calculated after integration of the acceleration signal. In what follows, the frontal punctual impedance recorded on a human head in vivo serves as a reference base for validating the theoretical and physical model. The natural frequency, damping, and de-coupled modal mass in accordance with the anteroposterior direction, serve as objective reference parameters in the validation process. The objective is then to prepare a theoretical and physical model able to reproduce the same modal behaviour as the human head.

MODAL ANALYSIS OF THE FEM - The method selected uses the finite element method, which makes it possible to characterize a distributed medium through its discretization. After the model is built we then carry out a theoretical modal analysis using an implicit finite element code (ALGOR). The problem analysed is that of looking for eigenvalues and eigenvectors of the rigidity and mass matrixes of the model. It should be mentioned that this calculation is made without any external force and that the results are thus intrinsic to the structure. After system discretization by finite elements, the equation governing the dynamic response is given according to Zienkiewicz (1973) as follows:

$$[M]\{\ddot{U}(t)\}+[C]\{U(t)\}+[K]\{U(t)\} =\{F(t)\}$$

where :

$\{F\}$ represents the sum of the external loads applied to the structure. In our case the value of $\{F\} = \{0\}$, since there are no external forces.

$\{U\} = \{u_i, i = 1, 2,...n\}$ where u_i are the generalised co-ordinates.

$[M]$, $[K]$ and $[C]$ are the mass, rigidity and damping matrixes of the structure.

$\{U(t)\}$ and $\{\ddot{U}(t)\}$ represent the structure nodal displacement and nodal acceleration vectors at instant "t".

This equation enables a solution type $U(t) = U_0e^{i\omega t}$. After simplification, it becomes : $[-\omega^2M + K]\{U\} = 0$

By making $\omega^2 = \lambda$, to each λ_i, a proper pulsation ω_i and an eigenvector $\{Ui\}$ are associated expressing the modal behaviour of the n°i vibration mode.

In the proposed approach, the mechanical properties of the materials making up the model are chosen to have theoretical modal parameters close to those given by the experiment. The viscous damping matrix which takes account of the viscoelastic properties of the cerebral material is introduced as a linear combination of the rigidity and mass matrixes, in order to obtain the damping given on the experimental curves. This matrix is defined by $[C] = \alpha[M] + \beta[K]$ with α and β reals in order to conserve the orthogonal properties vis à vis the mass and rigidity.

3D FINITE ELEMENT MODEL OF THE HEAD

MODEL CONSTRUCTION - The head anatomy is approached by imaging techniques using nuclear magnetic resonance. These images correspond to horizontal sections of the head at different heights. Eighteen 5 to 10 mm thick layers were meshed in the horizontal plane as shown in figure

1a, then assembled on top of one another to form a global 3D structure (figure 1b). In the following, the X, Y, Z, reference frame is orthonormed with the model centre of gravity as origin. The model is capable of distinguishing different head constituents intervening in the dynamic of the head, namely the skull, brain, cerebellum and cerebral trunk. The cerebral spinal fluid "CSF" is sub-divided into peripheral "CSF 1" which constitutes the brain-skull interface and "CSF 2" localised between the various cerebral elements. The model includes 4568 brick elements which model the brain and cerebral spinal fluid, 247 membrane elements to discretize the falx cerebri and tentorium cerebelli, and finally 1398 shell elements for modeling the skull. The thin layer modeling "CSF 1" between the brain and skull, is given by a viscoelastic material of low Young's modules (about 1.5% of the cerebral material module) and a Poisson ratio close to 0.5. To approach the behaviour of the mechanical liaisons between the various cerebral elements, the Young's modules of the "CSF 2" thin layer is considered to be about 15% of that of the brain.

For these models, the brain mass is 1.35kg. The mechanical parameters selected for the materials modeling the brain and skull come from the literature (Ward et al., 1975, Ruan et al., 1992). Those relative to "CSF" were established during the validation process and are thus considered as the problem unknowns. The final values of these parameters are reviewed in table 1.

THEORETICAL MODAL ANALYSIS - For the model validation process, the theoretical mode shapes at around 100 Hz of the various head vibration modes are illustrated by the iso-displacement curves in some parallel section planes with the three reference planes (horizontal, frontal, sagittal). These observation planes will not always be merged with the reference planes and will be able to be off-set in order to better illustrate the movements. The displacement vector amplitude is graduated from 0 to 100%.

The three first natural frequencies are at 89, 97, and 103 Hz. The mode shape of the first vibration mode, given in figure 2A shows a global rotation of the brain around the Z1 axis passing by the model centre of gravity, and forming an angle β_z of $\frac{\pi}{8}$ rad with the Z axis. The brain rotation movement is thus located in the perpendicular plane to the Z1 axis with maximum deformations located at the occipital and lateral regions. The mode shape of the second mode given in figure 2B expresses a rotation of the left hemisphere around the Y1 axis and of the right hemisphere around the Y1' axis. These two axes are symmetrical with regard to the median sagittal plane of the head and form angles of $\frac{\pi}{8}$ rad with the Y axis. Maximum deformations are located at the dome and frontal lobes. The mode shapes of the third mode given in figure 2C show a brain rotation around the X1 axis which gives an angle β_x of $\frac{\pi}{8}$ rad with the X axis and is thus perpendicular to the Z1 axis. The maximum deformations are located at the temporal lobes and skull dome.

In general, the head low frequency behaviour is characterized by three vibration modes illustrated by brain rotation around the Z1 and X1 axis (first and third mode) and rotation of the left and right hemispheres respectively around Y1 and Y'1 axis. These three modes have the specificity of setting virtually the whole cerebral mass in motion and situating themselves around 100 Hz. From all evidence, the mode excited during the experiment by frontal

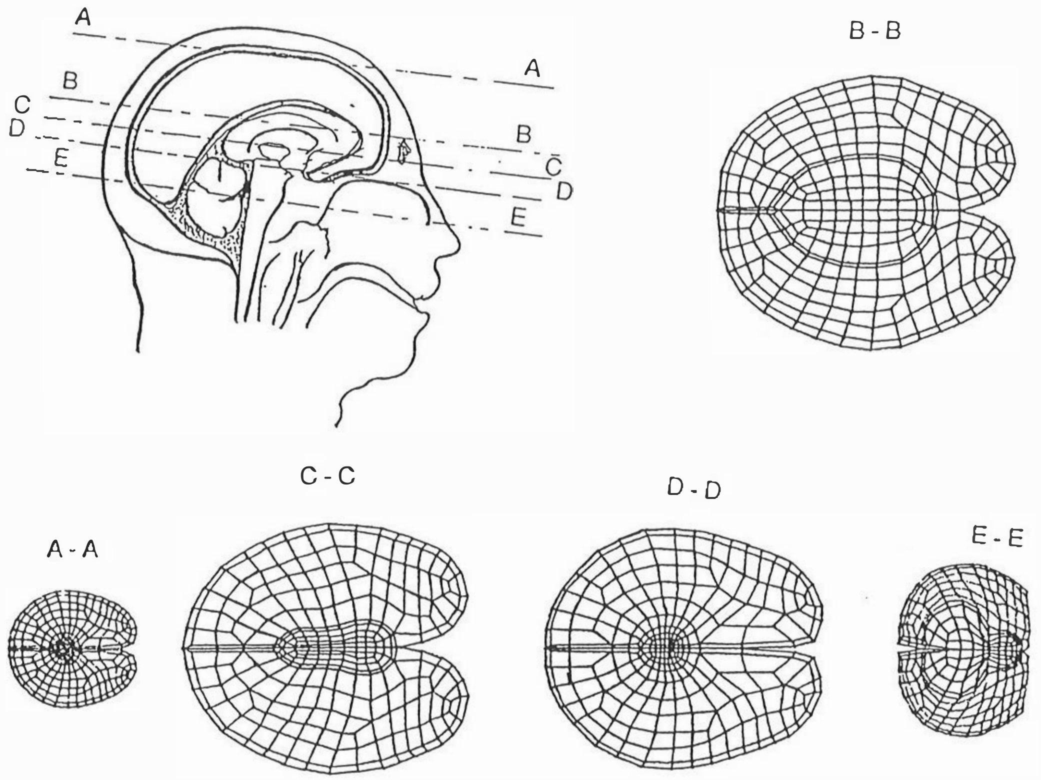


Figure 1a : View of the meshing of a few horizontal sections at various levels. The 3D model is made by assembling 18 sections of this type.

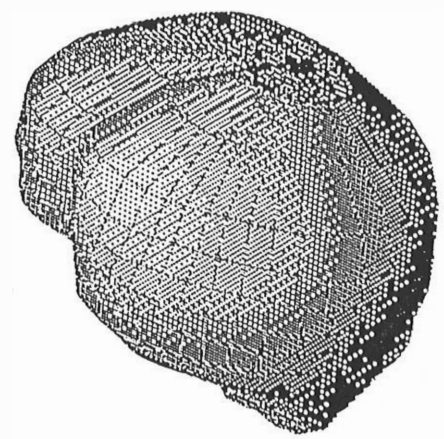
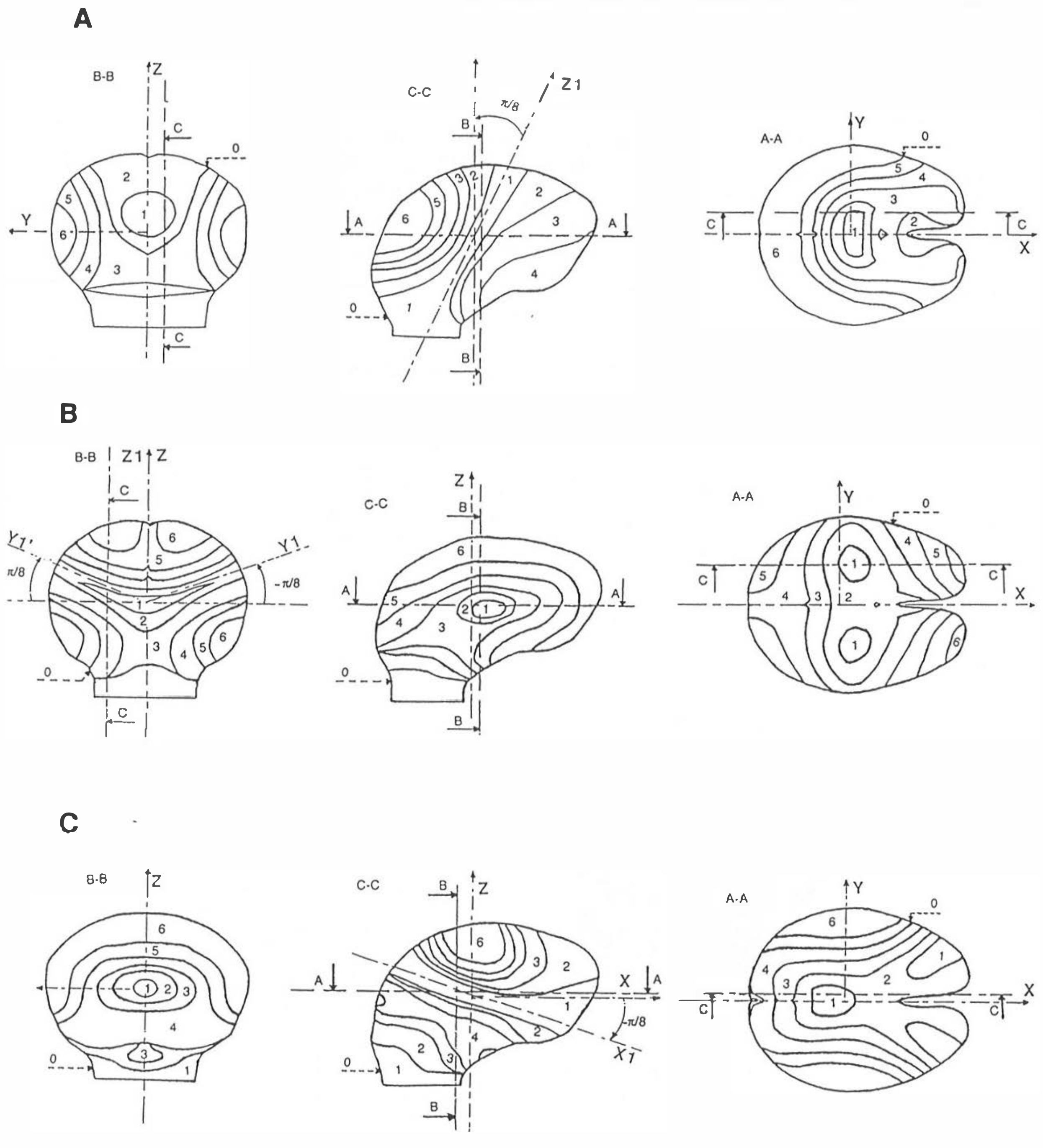


Figure 1b : Global view of the 3D finite element model of the human head.

Table 1 : Materials mechanical properties.

	Young's Modulus (kPa)	Poisson's Ratio	Mass Density. (Kg/m^3)
Brain	675	0,48	1140
CSF1	10	0,499	1040
CSF2	100	0,49	1040
Falx and Tentorium	31500	0,45	1140
Skull	50e+5	0,21	1500



0 - 0 % 1 - 17 % 2 - 33 % 3 - 50 % 4 - 66 % 5 - 83 % 6 - 100 %

Figure 2 : 3D Mode shapes of the finite element model.
A : Vibration mode at 89 Hz; brain rotation around the Z1 axis.
B : Vibration mode at 97 Hz; left cerebral hemisphere rotation around the Y1 axis and right cerebral hemisphere around the Y'1 axis.
C : Vibration mode at 103 Hz; brain rotation around the X1 axis.

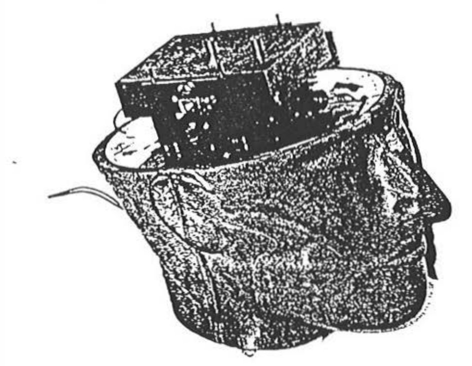
impact is the second mode since the movement occurs in the sagittal plane. This experiment validates this latter model in so far as the experimental modal parameters are very close to the theoretical values (natural frequency 100 Hz vs 97 Hz and a de-coupled mass of 1.4 kg versus 1.35 kg for the model).

By concentrating on low frequency behaviour (10 - 300 Hz), then as a first approximation the head can be modeled by a C2 body (of mass M2 and inertia I2 in relation to the Z axis) modeling the brain, fixed in a C1 body (of mass M1 and inertia I1 in relation to the Z axis) modeling the rest of the head. The visco elastic liaison system linking these two bodies has to be such that the complete unit has modal properties close to those recorded on the living person or numerically determined with the finite elements model.

PHYSICAL MODEL OF THE HEAD

MODEL PRESENTATION - A simple way of physically simulating such a dynamic behaviour is to consider two bodies C1 and C2 connected by cylindrical rods whose vibrations are dampened by elastomeric elements. By a suitable choice of rod dimensions and positioning, it is then possible to fix the translation vibration modes in any horizontal plane direction and to reproduce the relative torsion vibration around the vertical axis.

In practical terms the dummy head prototype was obtained by lightening an existing dummy head and fixing in its centre the C2 body which simulates the brain. The liaison between the two bodies is achieved by means of four steel rods of diameter d, length l arranged in a square configuration whose diagonal is 2h (figures 3, 4 and 5).



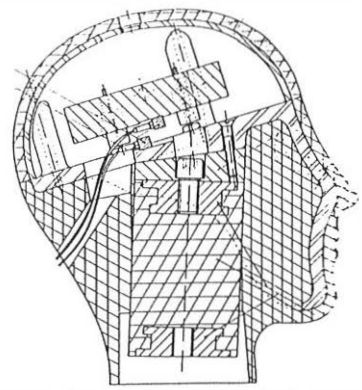


Figure 3 : General views of the physical head model

The following numerical values come from the theoretical modal analysis of the physical model as has been described above.

$M_1 = 2.68$ kg , $I_1 = 8.72$ kg m^2 $l = 28.10^{-3}$m $d = 2.10^{-3}$m

$M_2 = 1.28$ kg , $I_2 = 2.06$ kg m^2 $h = 2.5.10^{-3}$m

The dampening parameter (lying between 10 and 15%) was obtained by mounting the clamped rods in the elastomeric cylinders (Euladip 200) of diameter 10 mm and length slightly less than that of the rods.

TRANSLATION MODES - The translation modal behaviour of the structure described in figure 4 was analyzed using the Rayleigh method (Roseau 1978), by comparing the rods to beams under flexion. An x axis beam carrying additional masses μj at the abscissa points xj, shows a proper pulsation defined by:

$$\omega_0^2 = \mathrm{Inf}_{\xi \in K} \frac{\int_0^l EI\ddot{\xi}^2 dx}{\int_0^l \rho\xi^2 dx + \sum_{j=1}^{p} \mu_j \xi^2(x_j)} \quad (1)$$

with E = 21.10[10] Pa and μ = 7800 Kgm^{-3} being the material characteristics of the rods. In the flexion inertia of the rods (x), the equation of the elastic line of the rods. The sub assembly K1 generated by the K elements which satisfy the orthogonal condition is defined.

$$\int_0^l \rho\xi_0\xi dx = 0 \qquad \omega_1^2 = \mathrm{Inf}_{\xi \in K1} \frac{\int_0^l EI\ddot{\xi}^2 dx}{\int_0^l \rho\xi^2 dx + \sum_{j=1}^{p} \mu_j \xi^2(x_j)} \quad (2)$$

The first two vibration modes of this system will be determined to ensure that the first mode is in conformity with the desired simulation and that the second mode is sufficiently distant from the first one so that the decoupling hypothesis of the modes is justified.

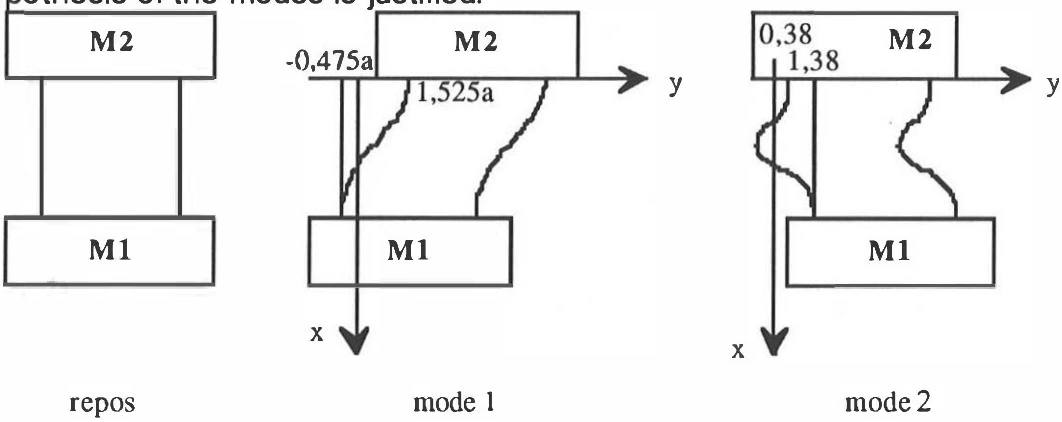


Figure 4: Translation mode shapes of the physical model of the head.

The equations of the mode shapes relative to the first two modes of figure 4 can be expressed as :

$$y_1(x) = \frac{a}{2}(\cos(\frac{\pi}{l}x) + 0{,}525) \quad (y = 0 \text{ for } x = \frac{M_1}{M_1 + M_2} l = 0{,}6759.l) \quad (3)$$

$$y_2(x) = \frac{4a}{3\sqrt{3}}(\frac{1}{2}\sin(\frac{8\pi x}{3\ l}) - \sin(\frac{4\pi x}{3\ l})) + pa \quad , \quad p \in \Re$$

Orthogonal condition signs: $$\int_0^l \rho\xi_0\xi dx = 0 \quad (4)$$

giving (with $\rho \neq 0$) $$p = -\frac{\int_0^1 \frac{4a}{3\sqrt{3}}(\frac{1}{2}\sin(\frac{8\pi x}{3\ l}) - \sin(\frac{4\pi x}{3\ l}))dx}{\int_0^1 \frac{a}{2}(\cos(\frac{\pi}{l}x) + 0{,}525)dx} = 0{,}3813 \qquad (5)$$

with the numerical values given above becomes:

$\omega_1 = 638$ rds^{-1} (or $f_1 = 101$ Hz) and $\omega_2 = 4133$ rds^{-1} (or $f_2 = 658$ Hz).

The translation modal behaviour in any horizontal plane direction is thus in conformity with the modal data from the experiment and from the 3D FEM in the frequency range 10 - 300 Hz.

ROTATION MODE - The C1-C2 relative torsion vibration mode must be at around 100 Hz, which fixes the diagonal of the square described by the position of the four rods in the X, Y plane (figure 5). In this case the rods function in flexion (displacment f and stiffener k) and in torsion (displacement q and stiffener kt).

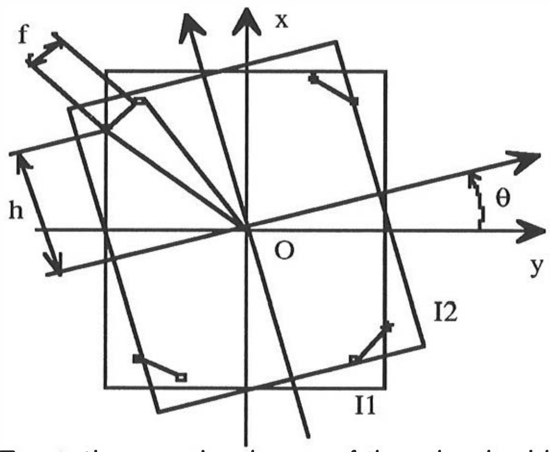


Figure 5 : Z rotation mode shape of the physical head model

By staying in the small displacement area we have : $f \approx \theta * h$

The torsional moments around Oz exerted by a rod and a damper on each mass can then be analyzed.

The elastic term is: $$M_k = hfk + k_t\theta \approx h^2k\theta + \frac{\pi G d^4}{32 l}\theta \qquad (6)$$

and the viscous term is given by: $$M_c \approx h(\frac{\partial(h\theta)}{\partial t}c) = h^2c\dot{\theta} \qquad (7)$$

From which the expression for both the stiffener and viscous resistance in torsion of the four connecting elements can be obtained. For the vibration torsion mode, the head can then be modeled as shown in figure 6.

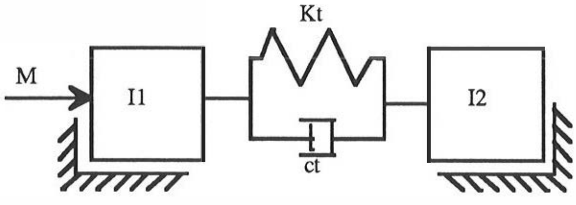


Figure 6 : Lumped model of the C1-C2 relative Z rotation phenomenon.

For the rods of length l and diameter d given in the previous paragraph the elastic and viscose components of the liaison which fixes the torsion of the brain in the skull can now be calculated.

$$-- K_t = h^2 \frac{3\pi E d^4}{4l^3} + \frac{\pi G d^4}{8l} \quad \text{and} \quad - c_t = h^2 c \qquad (8)$$

With G the shear modulus of steel G.

The impedance of this model corresponds to the ratio of the Fourrier transform of the rotational moment M(t) and the relative angular speed u(t) between the two masses

$$\overline{Z} = \frac{\overline{M}(\omega)}{\overline{\vartheta}(\omega)} = \overline{Z_1} + \frac{\overline{Z_2}\,\overline{Z_3}}{\overline{Z_2} + \overline{Z_3}} \quad \text{With} \quad \overline{Z_1} = j\omega I_1, \quad \overline{Z_2} = j\omega I_2, \quad \overline{Z_3} = c_t + \frac{K_t}{j\omega} \qquad (9)$$

In the same way as before the distance h separating the rods is adjusted in order to obtain a rotation resonance frequency at around 100 Hz.

The numerical application gives the diagonal of the installed square equal to 45 10^{-3}m in order to obtain a resonance frequency at 100 Hz in conformity to the results given by the FEM.

PROTOTYPE VALIDATION - The experimental validation of the prototypes dynamic behaviour was done in conformity with the method described above. The prototype's frequency response in any horizontal plane direction is given in figure 7. A decoupling of a mass of about 1.5 kg occurred at the natural frequency of 100 Hz, and a damped frequency of 10% (C = 22 N s m^{-1}).

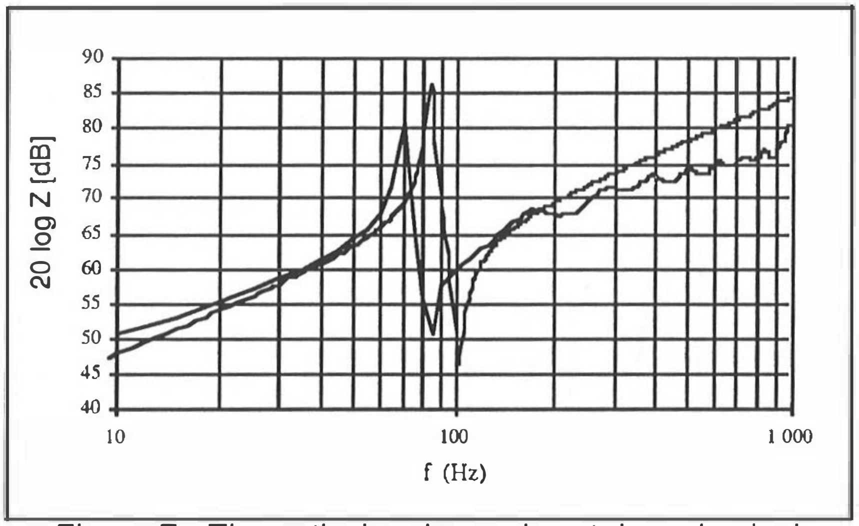


Figure 7 : Theoretical and experimental mechanical impedance of the dummy head prototype

The torsional mechanical impedance of the physical model is illustrated in figure 8. As revealed by the FE model, a torsional resonance was observed at 100 Hz accompanied by a decoupling of an inertia in the order of 2 kg m^2.

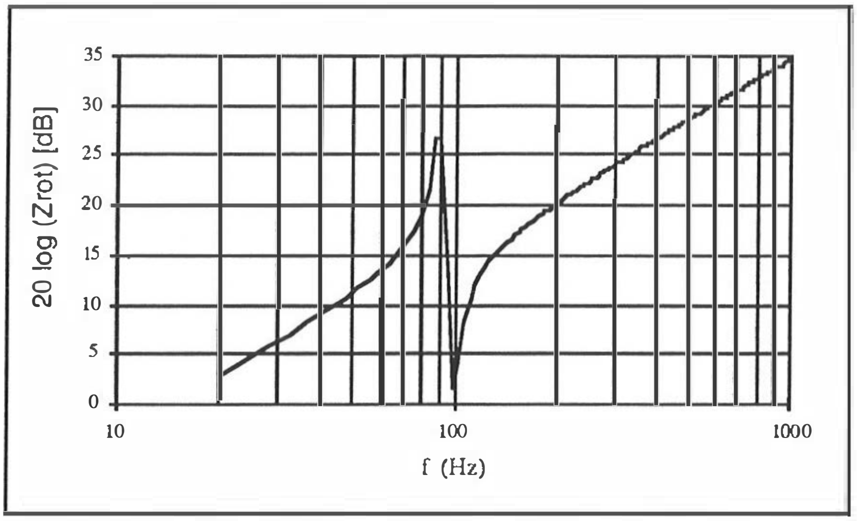


Figure 8 : Torsional impedance of the physical model

A temporal analysis of the prototype was carried out under frontal impact conditions with the aim of showing the "brain - skull" differential motion recording possibilities. An example of the temporal evolution of this "intracranial" parameter is given in figure 9. In this simulation, the shock was sufficiently short (8 ms) so that its spectrum excites the critical frequency of 100 Hz and causes "brain - skull" decoupling as was predicted by the modal analysis. These behavior validates the prototype in the 10-300 Hz frequency range given that its dynamical behavior is in conformity with the in vivo head frequency responses and with the FEM 3D modal analysis results.

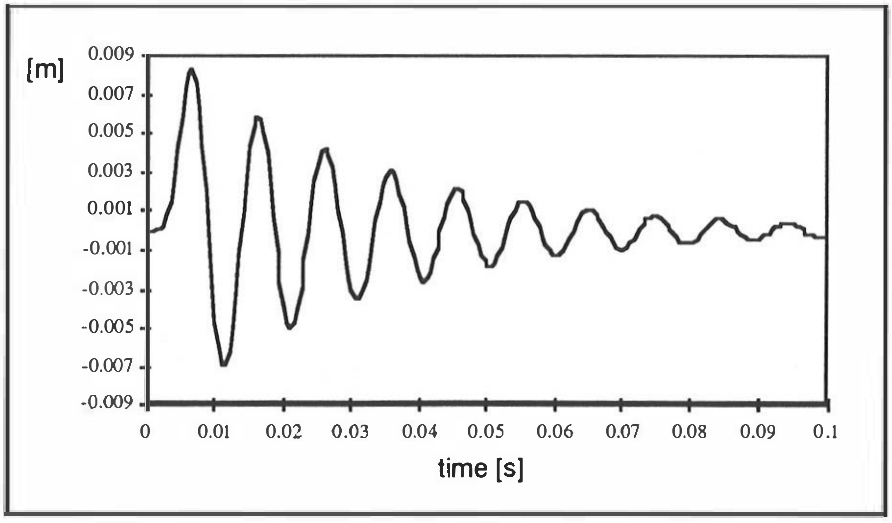


Figure 9 : Brain-skull relative displacement recorded for a high energy impact

DISCUSSION AND CONCLUSION

This study shows how the results from the experiment and from a new finite element model of the human head can be transposed onto a physical model resulting in the construction of a prototype dummy head. In this discussion the results and consequences relative to the proposed numerical and physical modeling will be presented successively.

At the theoretical level, a new 3D finite element model of the head has been built from meshing eighteen horizontal sections of the brain obtained by imaging techniques using nuclear magnetic resonance. the proposed model distinguishes six elements of the head: the skull, the cerebral spinal fluid which conditions the brain skull liaison, the cerebral hemispheres, the cerebellum, the cerebral trunk and the membranes. The model is validated by its theoretical modal analysis compared to the in vivo mechanical impedance recordings of the head. To the best of our knowledge this validation technique is the only one which is applicable to human beings. Further it would seem that no mode shape of a 3D finite element model was proposed, the modal analysis is an important step prior carrying out the incremental time analysis of the model in a shock situation. It illustrates the head dynamic behaviour and enables a prediction to be made of a certain number of lesion mechanisms through preferential movements of the structure revealed by the mode shapes.

This validation technique makes it possible to fix the brain-skull liaison conditions and model the sub-arachnoidian space using a low rigidity material (10 KPa) allowing a relative brain skull displacement .

The FEM adjusts the mechanical properties of the intersticial material so as to have a first natural frequency in the sagittal plane at about 100 Hz and the de-coupling of the whole brain. The results show three brain rotation-modes of vibration around the Z1, Y1-Y'1 and X1 axis respectively making an angle of $\frac{\pi}{8}$ rad with the Z, Y, and X reference axis. The calculated natural frequencies (89, 97, and 103 Hz) are compatible with the mechanical impedance recording of the head in vivo, and in agreement with the frequencies calculated on the 2D model of Ruan (1991), Willinger (1992) and Trosseille (1992) which respectively found 72 Hz, 150 Hz, and 98 Hz. The theoretical mode shape reproduces the brain-skull de-coupling observed in the experiment and is in agreement with the mode shape in the sagittal plan of the 2D model proposed by Willinger (1992). These results correspond to results existing in the literature, but complete the specifications of the head dynamic behaviour by the indispensable 3D consideration. The 3D mode shapes revealed in this analysis make it possible to better distinguish lesion mechanism as a function of the shock directional and temporal characteristics.

The transfer of results relative to these three vibration modes towards a dummy prototype head consists of imagining a dummy head within which "a cerebral mass" can vibrate in accordance with the translation and rotational degrees of freedom previously mentioned, whilst at the same time respecting the modal parameters determined in the experimental and theoretical study of the head.

This result was obtained by modifying an existing dummy head. The old version was lightened and a metallic "brain" was fixed to it using dampened elastic rods. The relative "brain - skull" movement is in conformity with expected results both for the translation in the horizontal plane as for the rotation around the vertical axis.

From the point of view of its dynamic validation, this model is more bio-faithful than existing models. Since its dynamic behaviour is very similar to that of the human head the recordings can be expected to be close to reality. The mechanical parameters thus accessible are, of course, the accelerations of the two masses present. These two parameters regulate the relative brain-skull movement which leads to peripheral focal lesions of the brain, stresses of the liaison systems which cause sub-dural haematoma and inertial brain loading which result in diffuse cerebral lesions. The totality of these parameters or these risks can be analyzed as a function of the shock type.

In addition to the model's intrinsic behaviour, the correct superimposition of its mechanical impedance with that of the living one, assures that at the moment of the shock, the impacted structure responds as if it had been struck by a human head.

In the validation phase, the mechanical impedance curve of the Wayne State Headform did not show a resonance frequency at 150 Hz, and behaved like a rigid body up to 500 Hz. If this result leads to the conclusion that a low bio-fidelity exists, it is important to mention that this model is nevertheless adapted when the shock spectrum is below 150 Hz, or when the shock duration exceeds about 20.10^{-3}s. In consequence this restriction defines an HIC validity area beyond which the acceleration of the head's centre of gravity is no longer valid, since several masses are in movement.

This research about the development of new theoretical and physical head models has thus shown the possibility of predicting the lesion mechanisms involved as a function of the damping characteristics of the shocks.

With this type of model it will be possible in the future to carry out a more in-depth analysis of the severity of a shock or the aggressivity of a structure in showing the lesion mechanisms likely to be released and the tolerance limit to be taken into consideration.

The main originality of these studies is that the head is no longer seen as a rigid body but as a non rigid composite structure. These results show that protecting the human head against a shock is not just a matter of dampening at any price, but "dampening" intelligently, by avoiding certain frequency ranges or certain temporal forms of the loading function. By this bias it will be possible to reduce the risk of a given lesion without increasing the risk of another type of lesion.

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