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Abstract

This report discusses the transformation and evaluation of the TUE head model from LS-Dyna into MADYMO. Results from both packages simulating Nahum's experiment were compared and showed reasonable agreement.. Furthermore a prescribed rotational motion of the head was assessed using the MADYMO deck and a sensitivity study into the hourglass parameter was conducted. From this it was concluded that the vonMises stress was more susceptible to this parameter then the pressure distribution. This effect was more evident in the rotational motion simulation than in the mostly translational (Nahum pulse) simulation. Finally a variation in the lower brainstem skull boundary condition was assessed showing that especially the pressure distribution was effected.

Contents

1. Introduction

In the ADRIA[1] project one of the focus points is head injury assessment. In the past a fair number of head models have been developed to facilitate these assessments. The TUE[2] has evaluated three of these head models: a global and a detailed version of the TUE model and the NHTSA[3] head model. The configurations were tested on their performance in a frontal impact (Nahum's cadaver experiment) and a rotational acceleration simulation. Comparison showed did not show one of the models to be significantly more accurate than the others [ADR98]. Because of its superiority in geometric and anatomic detail and its more refined mesh, the detailed TUE version was chosen for use in the victim head loading simulations. This head model was programmed in the LS-Dyna code and now needs to be transformed into MADYMO format. This report will discuss this transformation and the new format's performance when compared to the LS-Dyna model based on the Nahum's pulse response. Subsequently the MADYMO model was used to evaluate a prescribed rotational motion and to perform a sensitivity study into the hourglass parameter and the boundary condition regarding the lower brainstem and the skull.

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[1] Advanced crash Dummy Research for Injury Assesement
[2] Technische Universiteit Eindhoven
[3] National Highway Transport Safety Administration

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2. The LS-Dyna model

The TUE head model was originally developed in the implicit FE code MARC using the preprocessor MENTAT and then transformed to LS-Dyna (version 940) format. This section will describe the LS-Dyna model in more detail.

2.1. General

The model has the intracranial contents divided into different substructures, being the cerebrum, falx cerebri, tentorium cerebelli, cerebellum and brainstem. Furthermore the foramen magnum is incorporated, through which the brainstem exits the skull. The scalp has not been incorporated. An overview of the configuration is given in table 2.1.

Head structure	inc.	# elm.	interface type
scalp	–		
cranium (skull)			
viscerocranium (facial bones)	+	188	solid elements
neurocranium	+	3024	solid elements
-foramen magnum	+		opening in skull base
meningal layers & CSF			
dura mater	+	2536	solid elements
-falx cerebri	+	448	solid elements
-falx cerebelli	+	18	solid elements
-tentorium cerebelli	+	186	solid elements
brain			
cerebrium	+	6758	solid elements
corpus callosum		(included in cerebrum)	
cerebellum	+	732	solid elements
brainstem	+	202	solid elements

Table 2.1: Mesh configuration

The mesh is continuous, so that all the substructures are tied[4]. As a result of this no relative displacement is allowed between the dura and the brain surface.

Apart from the input load no dynamic or kinematic constraints have been imposed on the head. This implies that restriction of the head motion by the

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[4]An exception to this are the lower end nodes in the lower brainstem which are not tied to the skull. It is believed that tying these nodes to the skull is to be preferred when used in combination with the tied dura-brain interface.

neck is not modelled. In the short time interval that is simulated (10 ms) this influence is not considered significant [ADR98].

2.2. Material properties

The skull was modelled as a rigid structure, the meningal tissue and the brain tissue as linear elastic and linear visco-elastic respectively. The material parameters are listed in the table 2.2.

Structure	const. model	ρ [kg/m^3]	E [MPa]	K [MPa]	G_0/G_∞ [kPa]	τ [ms]	ν [-]
skull	rigid	—	—	—	—	—	—
meninges	lin. elastic	1130	31.5	—	—	—	0.45
brain	lin. visco elastic	1040	—	1860	34.4/17.2	10	0.2

Table 2.2: Material properties

2.3. Nahum simulation and results

Nahum's cadaver experiment was chosen to evaluate the model. In this experiment the frontal skull was hit with a rigid impactor. The impact force as measured from this experiment is translated to a pressure load by dividing it by the area covered by the frontal skull elements on which the load is applied. This load is used as an input for a flexible skull simulation. Based on the output from this simulation, this load can then again be translated into a prescribed velocity for the nodes in a rigid skull simulation. Figures 2.1 and 2.2 show the pressure and vonMises stresses derived from the simulation.
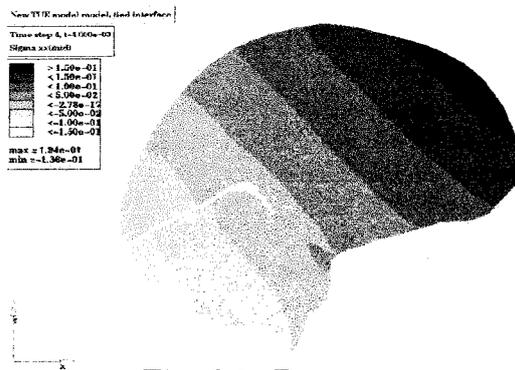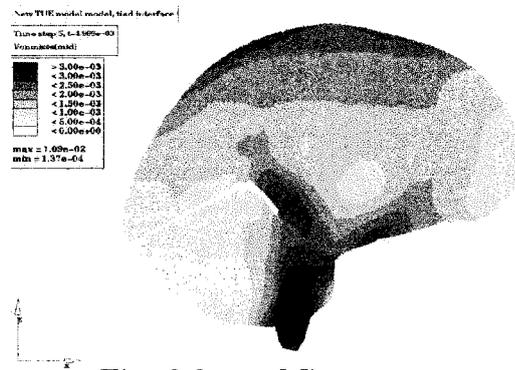

Fig. 2.1: Pressure

Fig. 2.2: vonMises stress

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3. The transition from LS-Dyna to MADYMO

The nodal coordinates and the elements were transformed from LS-Dyna into MADYMO 5.3 using Hypermesh. MADYMO 5.3 is the latest fully documented version and is readily available at the TUE.

3.1. The mesh and its constitutive properties

One problem with the resulting configuration was that the brain matter and skull were originally modelled as one mesh. The skull was made of rigid material and the brain as a mixture of linear elastic and linear visco-elastic material. MADYMO 5.3 however does not allow combination of rigid and other material in one mesh nor can two different meshes share the same nodes. Four possible solutions were considered:

1. Omission of the skull mesh and applying the motion to the dura nodes.

2. Duplicating the shared nodes and distributing them between the meshes thus enabling separation of the skull mesh from the brain mesh. Subsequently these meshes must be reattached.

3. Use elastic skull properties

4. Switch to MADYMO 5.3.1 where it is possible to combine rigid and other material properties in one mesh.

Option one is the crudest but it is not expected to influence the accuracy of the model, since the skull is considered rigid and prescribed motion can be applied to the dura. Option two allows for a more flexible model since the influence of a non-rigid skull and more advanced skull-dura interaction can be implemented in a later stage. Option three is viable but was considered costly in cpu time and this new setup would make comparison with the LS-Dyna more difficult. Option four was selected as it is fast to implement, allows for the modeling of the whole mesh and is expected to produce comparative output.

3.2. The prescribed motion

This also caused some problems. In MADYMO a motion cannot be applied to a rigid element mesh. Possible solutions are:

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1. Adding a multibody element in the brain with small mass and inertial properties, supporting the skull nodes to this body and subsequently applying the desired motion to this element.

2. Use elastic skull properties.

Option two was rejected on the same ground as in paragraph 3.1. Option one has been implemented. Because MADYMO requires either a displacement or an acceleration field as input for the motion of a multibody system, the LS-Dyna velocity input was differentiated and used as input.

3.3. Interfacing of lower brainstem nodes

The nodes in the lower brainstem were not tied to the skull in the original LS-Dyna model from which the results in this report are derived. This omission was later corrected. In order to make a fair comparison these nodes will not be tied in the MADYMO data deck as well. The deck however does include the possibility to tie these nodes and its influence on the output has been evaluated.

4. The MADYMO model

This section will describe the MADYMO TUE head model in more detail. The final code that was used to compile the data deck was MADYMO 5.3.2 Alpha 156 because this version uses an improved stress update algorithm. This algorithm prevents elements from building up stress in rigid rotation due to lack of objectivity, as was present in MADYMO 5.3.1.

4.1. General properties

Seen that the mesh is transferred directly from the LS-Dyna deck the mesh configuration are identical to those listed in table 2.1. For the material properties the values of table 2.2 are used.

4.2. The simulation test matrix

Two pulses are assessed in this report: Nahum's experiment, for comparison with the results derived from LS-Dyna, and a prescribed rotational motion. These are simulations N0.1F and R0.1F in Table 4.1.

The elements in the brain model are SOLID-1 elements. SOLID-1 elements only use one integration point in the centroid instead of one in each of the 8 corner nodes. This technique is called "integration reduction". Integration reduction is used by some simulation programs, such as MADYMO, in order to avoid "mesh-locking". This phenomenon can occur when incompressibility is used in combination with constraints and results into parts of the mesh becoming undeformable. A beneficial side effect of integration reduction is the reduced cpu time, a drawback is loss of accuracy. More importantly though: integration reduction introduces "hourglass modes". An hourglass mode is a special deformed state of an element in which its energy is equal to zero. In order to suppress these modes MADYMO uses an "hourglass parameter". This parameter works likes a spring when it stabilizes the element through suppression of the hourglass modes. The hourglass parameter should be set as low as possible as it lowers the accuracy of the solution. A rule of thumb is: "Hourglassing should only roughly dissipate 10% of the total internal energy dissipated by the model".

In MADYMO the hourglass parameter effects the element stiffness only. Admissible values range from 0.0 to 0.5, while 0.1 is the default value. A difference with the LS-Dyna deck is that in that configuration it was chosen to use an hourglass parameter based on viscous in stead of elastic behavior. To investigate the influence of this parameter on the results both the Nahum pulse and the rotational pulse were computed at two different values of this parameter. These are simulations N0.01F and R0.01F in Table 4.1.

To investigate the influence of the applied boundary condition to the lower end of the brainstem and the skull, simulation N0.1T was performed. This simulation has the same setup as simulation N0.1F with the exception of the interface type.

simulation	pulse	Hourglass	boundary condition
N0.1F	Nahum	0.1	free
R0.1F	rotational	0.1	free
N0.01F	Nahum	0.01	free
R0.01F	rotational	0.01	free
N0.1T	Nahum	0.1	tied

Table 4.1: Test matrix

For all test the time step was $1E^{-5}$ [s] and the integration method Euler. For simulation N0.1F 20 frames were written to the kinematics files and 100 points to the time-history files. For the other simulations 10 frames to the kinematics files and 100 points to the time-history files.

4.3. Nahum's experiment simulation

Simulations N0.1F and N0.01F describe Nahum's experiment with hourglass parameter set at 0.1 and 0.01 respectively. These simulations will be used for comparison with the LS-Dyna output and to investigate the influence of the hourglass parameter in this primarily translational motion.

4.3.1. Results simulation N0.1F

Figures 4.1 and 4.2 show the pressure distribution and the vonMises stress distribution.
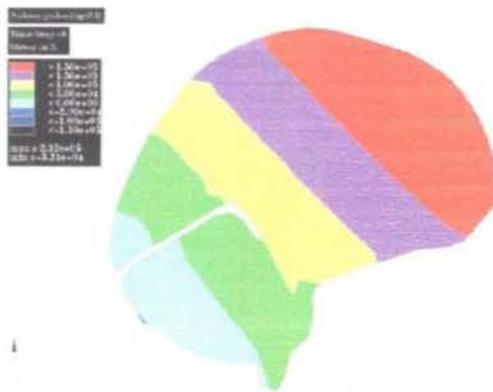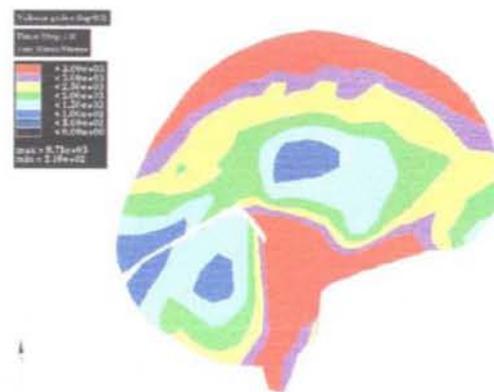

Fig. 4.1: Pressure   Fig. 4.2: vonMises stress

This result is in reasonable agreement with the LS-Dyna output. The pressure distribution shows a similar gradient buildup with a shift towards the contre coup region. In the coup and contrecoup region the MADYMO model shows a more constant pressure than the LS-Dyna model. In the vonMises stresses however the MADYMO model shows a larger spread of values. In Annex A time-history plots of the coup and contre coup elements for pressures are depicted.

4.3.2. Results simulation N0.01F

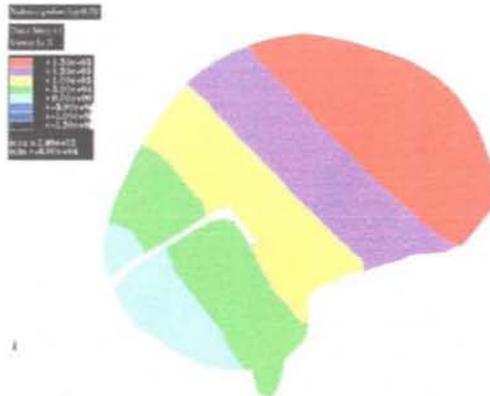Figures 4.3 and 4.4 show the pressure distribution and the vonMises stress distribution.
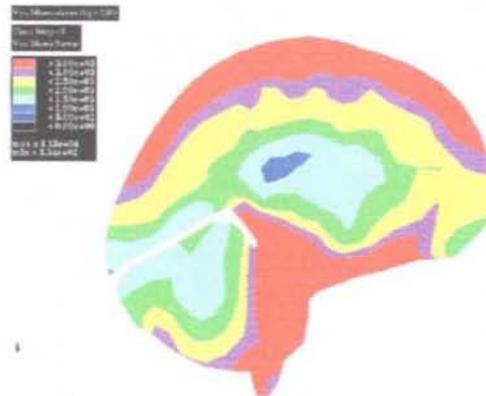
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Fig. 4.3: Pressure

Fig. 4.4: vonMises stress

This simulation also shows reasonable agreement with the LS-Dyna model. When compared with Figures 4.1 and 4.2 it can be concluded that the lower hourglass parameter has a negligible effect on the larger influence on the pressure distribution and only a small influence on the vonMises stress. In Annex A time-history plots of the coup and contre coup elements for pressures are depicted.

4.4. Rotation simulation

Simulations R0.1F and R0.01F have a rotation as input. The prescribed rotational motion shown in Fig. 4.5 is applied in posterior-anterior direction.
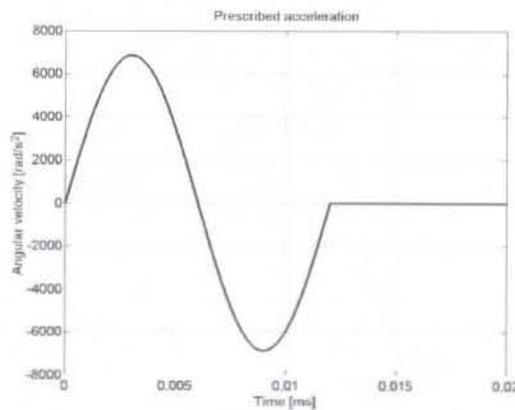

Fig. 4.5: Prescribed rotational motion

Two values of the hourglass parameter (e.g. 0.1 and 0.01) have been assessed in order to learn more about the influence of this parameter in this type of motion.

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4.4.1. Results simulation R0.1F

Figures 4.6 and 4.7 show the pressure and vonMises stress distribution

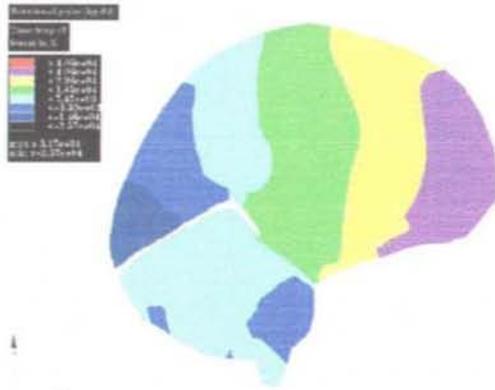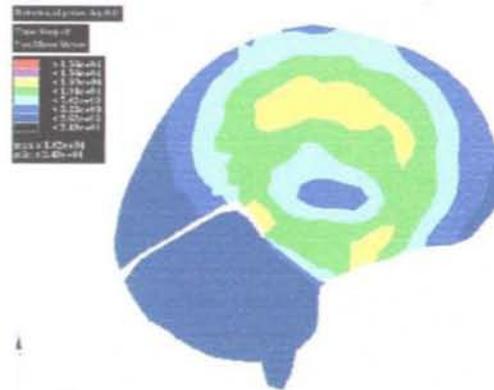Fig. 4.6: Pressure

Fig. 4.7: vonMises stress

4.4.2. Results simulation R0.01F

Figures 4.8 and 4.9 show the pressure and vonMises stress distribution for the rotational motion with hourglass parameter set at 0.01.
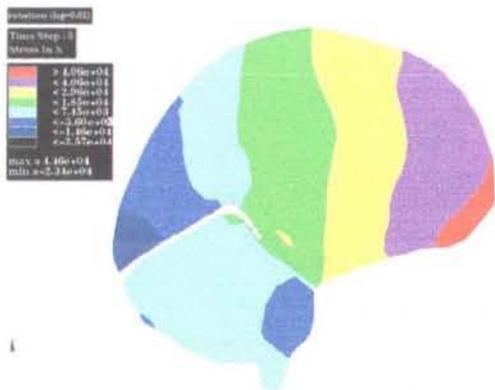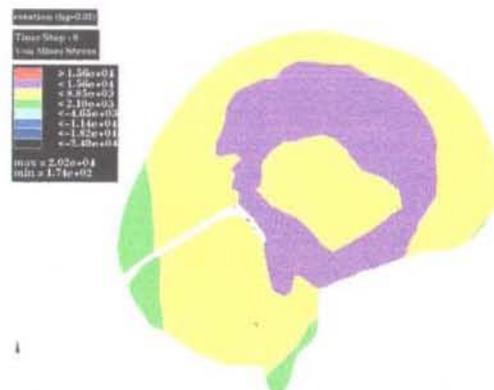

Fig. 4.8: Pressure

Fig. 4.9: vonMises stress

When compared to figures 4.6 and 4.7 it can be concluded that again the lower hourglass parameter does not influence the pressure distribution significantly. The vonMises stress is somewhat harder to compare since the color labeling in these to plots does not scale in precisely the same manner. But clearly simulation R0.1F shows greater differentiation between the vonMises stress levels and lower stress levels.

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4.5. Boundary condition type simulation

Simulation N0.1T has been performed to investigate the influence of the boundary condition of the lower end of the brainstem with respect to the skull (e.g. free versus tied). To this end it can best be compared to the output of simulation R0.1F were all the other parameters are set equal to those in simulation N0.1T.

4.5.1. Results simulation N0.1T

Figure 4.10 shows the comparison between simulations N0.1F and N0.1T.
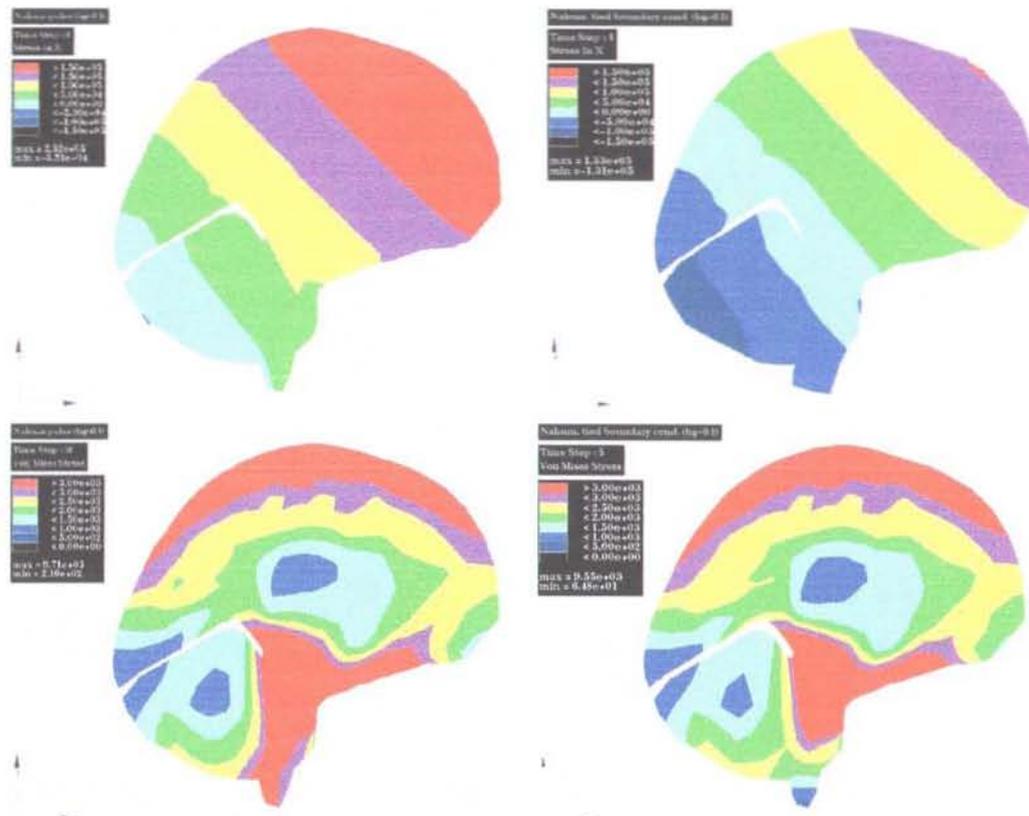

Fig. 4.10: Comparisson between free (left) and tied (right) boundary condition.

The pressure distribution shows a clear shift in pressure distribution with more negative pressures and less positive pressures in the tied boundary condition simulation. The vonMises stress shows largely the same response with the only clear exception in the lower brainstem region where the boundary condition is active.

5. Discussion and conclusions

Discrepancies between the LS-Dyna output and the MADYMO output can be accounted to:

- The transition of the velocity input in LS-Dyna to an acceleration input for MADYMO.

- The difference in hourglass control parameter type, viscous in LS-Dyna versus elastic in MADYMO.

6. Suggestions

To further investigate the first of the two possible causes of the discrepancies between MADYMO and LS-Dyna output, one can compare the velocity, displacement or acceleration of a node in the skull mesh with the LS-Dyna output. When these are identical, the motion of the skull meshes are identical and this probable cause can be eliminated.

More parameter variation of the hourglass parameter in both simulations would be convenient to gain more insight in it's influence. Recommended values for these simulation would be 0.45 and 0.001.
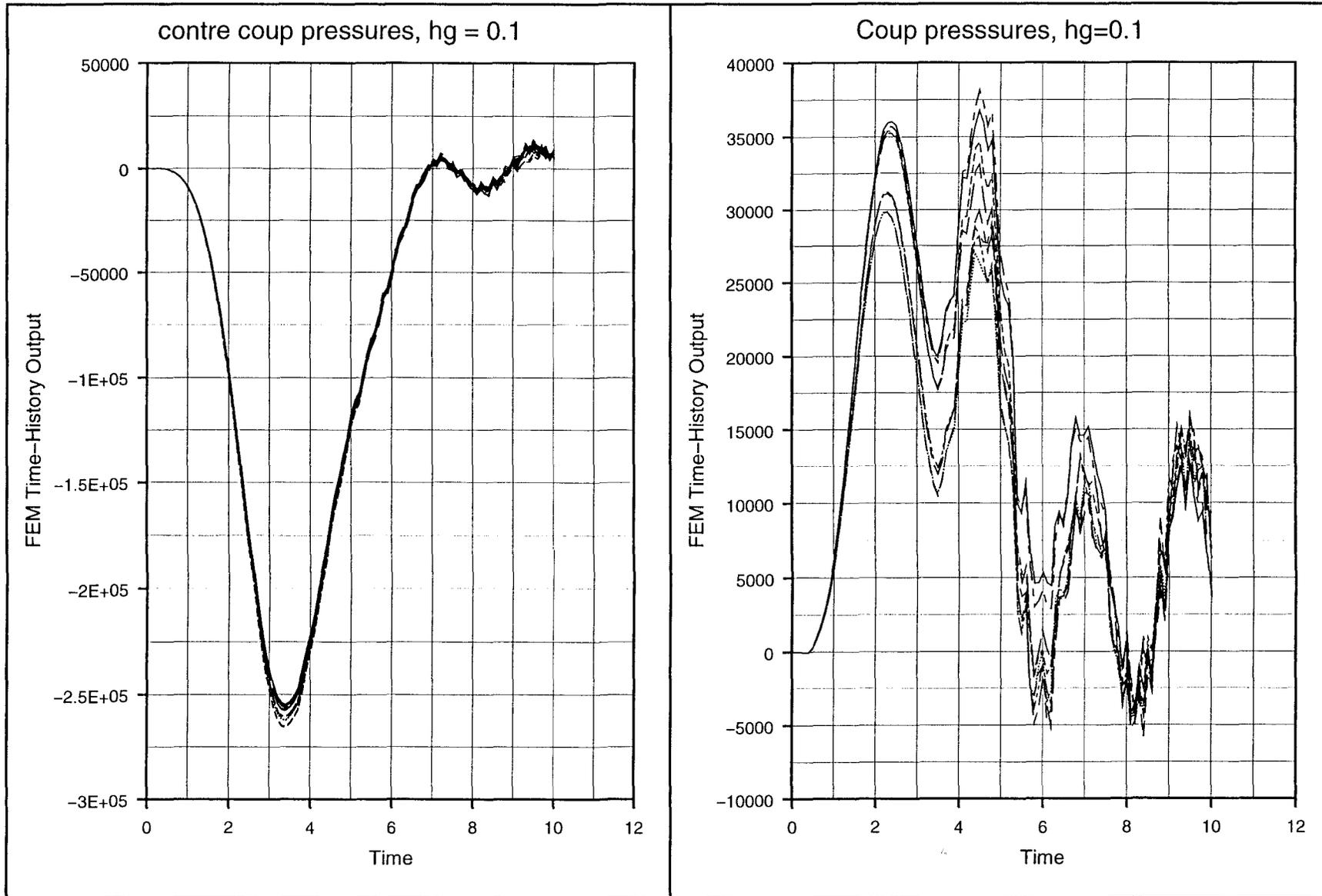
Also would it be interesting to further experiment with the boundary conditions of the lower brainstem and the skull. For instance: only tying the outer lower brainstem nodes to the skull, leaving the middle nodes free.

Lastly: separation of the dura mesh from the brain mesh as proposed in paragraph 3.1 would allow for a more realistic contact algorithm to be applied to this contact in the future.

References

[1] ADRAI deliverable report D3: "Computer model for victims head" (status: restricted), Transport RTD Programme of the 4th Framework Programme, project Nr: PL96-1074, Dec 1998.

[2] TNO Road-vehicles Institute, *MADYMO theory manual version 5.3*, TNO 1994.

[3] TNO Road-vehicles Institute, *MADYMO users manual*, TNO 1994.

FEM Time-History Output-1

contre coup pressures, hg = 0.1

Coup presssures, hg=0.1

FEM Time-History Output-1

Contre coup side, hg = 0.01

Coup side, hg = 0.01