A closed simple head model

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A closed simple head model: experimental and numerical analysis

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Abstract

At the Technische Universiteit Eindhoven a research program is set up with the title "Determination of the dynamical behavior of brain tissue during impact loading". A numerical head model is developed in MADYMO, to determine the local response during an impact load [3]. This numerical model is partly validated using a simple physical head model. This physical model consists of a cup filled with a silicon gel, that represents the human brain, covered with a perspex plate. This cup is rotated over 2 rad in 38 ms. The gel is visco-elastic and described by a four-mode Maxwell model. The dynamical response of the gel can be visualized using markers and a high speed camera.

Experiments with the covered cup are done. This results in relative rotation of the markers with respect to the cup. This maximum relative rotation is 0.27 rad.

Simulations of the experiments are done using a finite element model in MADYMO. The relative rotation is a factor 13-18 lower than in the experiments. Furthermore the relative rotation is oscillating at a high frequency.

To investigate this phenomenon several parameters, that contribute in the conversion from the physical to the mathematical model or in the conversion from the mathematical to the numerical model are varied. None of those changes resulted in a simulation that has the same trend as found in the experiment. It seems that it is not possible to simulate this experiment using the elements that are available in MADYMO.
Chapter 1

Introduction

In crash situations, the head is considered to be the most critical part of the human body. Investigation is done to get insight in the relation between a mechanical load on the head and the internal response of the contents of the head. Since it is not possible to measure internal response in an in vivo head during impact, numerical models can be used to predict the response of the head during an impact. To validate these numerical models, physical head models can be used.

At the Technische Universiteit Eindhoven a research program is set up with the title "Determination of the dynamical behavior of brain tissue during impact loading". A numerical head model is developed in MADYMO, to determine the local response during an impact load [3]. This numerical model is partly validated using a simple physical head model. This physical model consists of a cup filled with a silicon gel, that represents the human brain, covered with a perspex plate. This gel is visco-elastic and described by a four-mode Maxwell model. The dynamical response of the gel upon a transient rotation of the cup can be visualized using markers and a high speed camera.

Experiments with this cup are done before by Bax[1] and Bressers[2]. They used the same cup and gel, but didn’t use a cover. This resulted in a large three dimensional movement of the gel. To suppress this movement and model the enclosure of the human brain in a skull, the cover is added to the cup in this study.

In this research first experiments are done to measure the response of the gel in the covered cup (Chapter 2). These experiments are simulated in MADYMO using a finite element model (Chapter 3). Since the results of the simulation differ from the experimental results, several parameters are varied to trace the error. This is described in chapter 4. Finally a conclusion and some recommendations are made in chapter 5.
Chapter 2

Experiment

2.1 Set-up

A cup is filled with silicon gel, covered by a perspex plate and subjected to a fast rotation, using a spring driven loading device as used by Bax[1] and Bressers[2]. Some facts of the cup are summed here:

- Material: the cup is made of polyester and the cover is made of perspex.
- Dimensions: the inner-radius is 35 mm, the depth 29 mm. The volume is 106.10 ml. The wall-thickness is 6 mm.
- The cover has thickness 2.5 mm and is tightened to the cup using five bolts.
- The weight of the empty cup is 114.89 g. The empty cup with cover and bolts weighs 133.26 g.
- The cup is filled with silicon gel (Dow Corning, Sylgard 527, A&B)

2.2 Preparation of the experiment

The first day the gel is made by mixing component A and B 1:1 and stirring for about 15 minutes. After that, the cup is filled half and the gel is left hardening for a night. The second day the markers are placed and the rest of the cup is filled with the gel. When the air bubbles are gone, about four hours later, the cover is placed and tightened with the bolts. The markers are placed on the cover and the gel is left hardening for two weeks. More details can be found in Klomp[4]. Unfortunately after the cover was tightened new air bubbles appeared in the gel. Therefore it was not possible to trace all the markers. A top and side view of the cup is shown in figure 2.1. The markers that are traced are numbered.

Before analyzing of the results can be done, the co-ordinates of the markers on the cup are measured very accurately. This is done by placing the cup on an X,Y-table of e.g. a milling machine. Using a microscope with a view finder, the co-ordinates of the centre of the marker can be measured using the digital read-out of the miller. After this measurement, the cup is placed on the rest of the set-up and a camera is placed above the center of the cup. The optical axis of the camera is oriented along the cup axis by visual inspection.
2.3 Measuring

The cup can be fixated using a pin. Then a spring, that is connected to the cup, can be elongated using a ratchet-wheel. The loading of the spring is measured in ticks of the ratchet-wheel. After the fixation-pin is removed the cup rotates about 2 rad.

The deformation history of the gel is determined using marker tracking. To do this, markers are placed in the gel and on the cover. During the experiment these markers are recorded by a high-speed camera (4500 fps). The images are post-processed using Matlab as described by Roersma[3].

2.4 Postprocessing of the results

The images of the camera are imported in Matlab. The co-ordinates of the markers are measured using image processing techniques[3]. When a small angle between the camera’s optical axis and the cup axis exists, the imaging software accounts for the error by using the reference co-ordinates of the markers. The result is the displacement history of the markers in the gel with respect to a cup fixed cylindrical co-ordinate system.

2.5 Experimental results

Experiments are done with a spring-load of 4 ticks. The trajectories of the markers can be found in figure 2.2. It can be seen that the markers’ displacement is mainly angular.

The history of the relative rotation of the markers with respect to the cup can be found in figure 2.3. The solid lines show the relative rotation of the markers 3 and 4 of figure 2.1. These markers have the largest distance to the air bubble. The dashed line is the rotation of the cup multiplied by 0.1. At t=0, the cup starts to rotate. The markers have a delay in rotation with respect to the cup. This delay reaches its maximum after 16-18ms. At t=38 ms, the cup is suddenly stopped, because it reaches its end-stop. The marker’s rotation exceeds the cup rotation, which causes the negative peaks.
Figure 2.2: Trajectories of the markers during the experiment

Figure 2.3: Relative rotation of the markers at 4 ticks
2.6 Discussion

To investigate the influence of the cover these experiments are compared with the experiments done by Bressers[2]. The angular velocity of the cup during the last 10 ms before the cup reaches its end-stop, is determined graphically. This angular velocity is about 84 rad/s for both the experiment described in this chapter and Bressers' experiments. The radial position of marker 3 in figure 2.1 is 25 mm, the radial position of marker 4 is 12 mm. Bressers used three markers in his experiment. Marker 1 at a radius of 28 mm, marker 2 at 19 mm and marker 3 at 12 mm.

![Figure 2.4: The relative rotation of the markers in the open cup (4 ticks) as found by Bressers. Copy from [2]](image)

To compare both experiments the relative rotation of the marker at 25 mm can be interpolated between the markers at 19 mm and 28 mm. The markers at 12 mm can be compared directly. In the experiment with the covered cup, the maximum relative rotation of this marker is 0.27 rad. Bressers found for the open cup a maximum relative rotation of 0.49 rad. For the marker at a radius of 25 mm, the maximum relative rotation is 0.11 rad. Interpolating Bressers’ results, the maximum relative rotation is about 0.22 rad. There are several reasons for this effect. Bressers found a displacement in axial direction. Because the cover is made of material stiffer than the gel, this three dimensional displacement does not occur as much as it did with the open cup. An other reason is the place of the markers. Bressers placed the markers on top of the gel, while in the closed cup the markers are located at half the height.

Since Klomp[4] also used a closed cup these experiments are more similar to the experiments described in this chapter. Klomp used a covered cup with an inner radius of 33.5 mm, with the markers at half the height. The angular velocity of this cup during the last 10 ms before the cup reached its end-stop was about 105 rad/s. To fixate the cover to the cup, Klomp used tape in stead of bolts. Therefore the three dimensional movement of the gel is less suppressed, than by using bolts to tighten. Experiments with the cup Klomp used, resulted in a maximum relative rotation of 0.38 rad for markers at a radius of 12 mm, and 0.20 rad for markers at a radius of 25 mm. It can be concluded that the differences in relative rotations between the covered cup with bolts and the cup Bressers used are mainly due to fixation of a cover. Also the place of the markers in the gel is a contributing factor.
Chapter 3

Reference model

To simulate the rotating cup a Finite Element Method (FEM) model is made. Comparing this numerical model with the experiments done in chapter 2, provides information of the validity of numerical models of the human head. The mesh is made in Hypermesh v3.1 and exported to MADYMO 5.4.1.

3.1 Methods

3.1.1 Mathematical model

The FEM model consists of a cylinder representing the gel. Since it is assumed that no slip occurs between the gel and the cup and between the gel and the cover, it is sufficient to model the gel only. The material behavior of the gel is described using a viscoelastic, four-mode Maxwell model, with the parameters of table 3.1. The bulk modulus of the gel is $1.0961 \cdot 10^9$ Pa.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$i$ & $G_i$ [Pa] & $\tau_i$ [s] \\
\hline
1 & $2.7599 \cdot 10^4$ & $9.7434 \cdot 10^{-5}$ \\
2 & $1.7172 \cdot 10^4$ & $2.1563 \cdot 10^{-3}$ \\
3 & $3.7879 \cdot 10^2$ & $2.4705 \cdot 10^{-2}$ \\
4 & $1.2232 \cdot 10^3$ & $3.0977 \cdot 10^{-1}$ \\
$\infty$ & $2.164095$ & $-$ \\
\hline
\end{tabular}
\caption{Four-mode Maxwell parameters, copied from [2].}
\end{table}

All the outer surfaces are fixed in all directions to a rotating co-ordinate system. The rotation of this co-ordinate system is determined from the experiment i.e. the dashed line of figure 2.3.

3.1.2 Numerical implementation

The FEM model consists of 8832 SOLID1 elements. These elements use reduced integration. Therefore some zero-energy modes are possible. In order to prevent this to happen, MADYMO uses an Hourglass parameter. This parameter can be varied between 0 and 0.5; the default value of 0.1 is used in this simulation. In figure 3.1 the mesh is shown. The time step used in the calculation is $8.5 \cdot 10^{-7}$ sec, which results in 70591 increments. The total CPU time used for this calculation is 14074 seconds (almost four hours).
3.1.3 Data processing

To compare the results of the experiment with the FEM simulation, the displacements of the nodes on line M-M of figure 3.2 are exported. This line has the same X and Y co-ordinates as line A-A on figure 3.1.

The nodal displacement data are imported in Matlab. Now it is possible to plot the relative rotation of the nodes in the middle plane. The conversion from nodes of the numerical model to markers of the experiment can be done by linear interpolation. Since SOLID1 elements are used in the model, the relation between two nodal displacements is linear. Therefore the displacements of the nodes are interpolated so they can be compared to the markers with the same radii in the experiment, without losing accuracy [2].

3.2 Results and discussion

The relative angular displacement of the interpolated markers as a function of time is plotted in figure 3.3. The two solid lines simulate two of the markers in the gel, having the same radial position as marker 3 and 4 in chapter 2. The dashed line is the rotation that the cup experiences multiplied by 0.1.

The displacement of the markers in the simulation is quite different than in the experiment. In the first 38 ms, before the cup reaches its end-stop, the maximum relative rotation of marker 1 is 0.016, which is a factor 17 lower than the maximum relative rotation of marker 4 in the experiment. The maximum relative rotation of marker 2 is 0.0083, which is a factor 13 lower than the maximum relative rotation
Figure 3.3: Relative rotation of marker 1 and 2 in the reference simulation

of marker 3 in the experiment. Also the relative marker rotation is rapidly altering
between a positive and a negative value in contradiction to the experiment. After
the cup reaches its end-stop the relative rotation of the markers is fluctuating heavily
in both positive and negative direction. It is possible that a kind of locking of the
elements occurs.

3.3 Conclusion

The results of the simulation differ a lot from the results of the experiments. The
maximum relative rotation of the markers with respect to the cup in the experiment
is a factor 13-17 higher than found in the simulation. Therefore it is necessary to
vary some factors to trace the error.
Chapter 4

Parametric study

Errors are possible in the conversion of the physical model to the mathematical model and in the conversion from the mathematical to the numerical model. Examples of the first type of errors are the modelling of the cover and modelling of air-bubbles in the gel. The second type of errors contains e.g. errors in the mesh and the hourglass parameter. First the numerical variations are discussed, then the mathematical variations.

Variations are made using two reference models. Because the midplane of the model discussed in chapter 3 is a plane of symmetry, it is possible to model only the lower part of the cup. This is done to reduce CPU time. This model consists of 4416 SOLID1 elements. Boundary conditions are prescribed on the nodes in the plane that represents the midplane of the full cup. These nodes are not allowed to move in axial direction because of the symmetry conditions. The mesh of this model can be found in figure 4.1.

Figure 4.1: The mesh of the model of the half cup with 4416 elements

The history of the relative rotation of this model is similar to the history of the relative rotation of the full model and can be found in figure 4.2. Since there are no differences in these two reference models, both can be used arbitrarily. To reduce the CPU time, the simulations are run for the first 30 ms only.

A summary of the factors varied is displayed in table 4.1. Figures of the relative rotation as a function of time can be found in Appendix A.
Figure 4.2: *Relative marker rotation of the model of the half cup with 4416 elements*

Table 4.1: *Variations made on the reference simulation*

<table>
<thead>
<tr>
<th>Variation</th>
<th>Reference</th>
<th>Change</th>
<th>§</th>
<th>Fig.</th>
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</thead>
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<tr>
<td>Mesh refinement</td>
<td>full model, 8832 elements</td>
<td>±8 1104 elements</td>
<td>4.1.2</td>
<td>A.3</td>
</tr>
<tr>
<td></td>
<td>half model, 4416 elements</td>
<td>±4 1104 flat elements</td>
<td>4.1.2</td>
<td>A.4</td>
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<tr>
<td></td>
<td>full model, 8832 elements</td>
<td>×8 70656 elements</td>
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<td>A.5</td>
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<td>±10 Hourglass 0.01</td>
<td>4.1.3</td>
<td>A.6</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+100 Hourglass 0.001</td>
<td></td>
<td>4.1.3</td>
<td>A.7</td>
</tr>
<tr>
<td></td>
<td>Hourglass 0.5</td>
<td></td>
<td>4.1.3</td>
<td>A.8</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>half model, Bulk modulus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G_{\infty}, G_1, \tau_1, \ldots G_4, \tau_4 \div 10$</td>
<td>+100 Bulk $1.0961 \cdot 10^9$</td>
<td>4.2.1</td>
<td>A.10</td>
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<td>no BC's on midplane</td>
<td>4.1.1</td>
<td>??</td>
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<td>Air bubble model</td>
<td>full model 8832 elements gel</td>
<td>1 element air</td>
<td>4.2.2</td>
<td>A.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 elements air</td>
<td>4.2.2</td>
<td>A.13</td>
</tr>
<tr>
<td>Cover model</td>
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<td>top-layer gel replaced by perspex</td>
<td>4.2.3</td>
<td>A.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>one layer SHELL4 added</td>
<td>4.2.3</td>
<td>A.15</td>
</tr>
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</table>
4.1 Numerical variations

4.1.1 General check of the numerical model

To check whether mistakes are made somewhere in the input file, the boundary conditions for the model of half the cup are changed. The nodes of the midplane in the reference situation are restricted to move in axial direction. This restriction has been removed in this simulation. This situation is identical to an open cup with half the height. The results of this output are comparable with the results of the open cup as found by Bressers[2] shown in figure 2.4, taken into consideration that the cup only has half the height of the cup Bressers used. The relative rotation as a function of time is shown in figure 4.3. It can be concluded that there are no errors in the input file, that might have influenced the results.

![Figure 4.3: Relative rotation of the situation where midplane nodes are allowed to move in axial direction](image)

4.1.2 Mesh variations

To examine the influence of the mesh on the results the mesh is refined 8 times and the mesh is made less dense. An existing mesh of 1104 elements is used to investigate the influence of larger elements. This mesh is shown in figure 4.4. For marker 1, the maximum relative rotation is increased by a factor 1.3 with respect to the reference model. For marker 2, an increase of a factor 2.0 is found. The results are displayed in figure A.3.

Because there are only three layers of elements from the bottom to the middle of the cup the nodes on the midplane is possibly restricted in their movement. Therefore a new model is made that consists of half a cup with 1104 elements. The height of the elements is reduced by a factor two. It is shown in figure 4.5. It is expected that the nodes on the midplane can make a larger relative rotation. Instead of that, it is found that the relative rotation is decreased by a factor 1.03 with respect to the reference situation for both the markers. This is probably due to the fact that the elements are not more or less cubic anymore. The results can be found in figure A.4.

The mesh is refined eight times, to evaluate the result of small elements. In this simulation the maximum relative displacement for marker 1 is 0.01297, which is a factor 1.2 lower than the reference situation. For marker 2 the maximum relative rotation is 0.004799, which is a factor 1.7 lower than the reference situation. The
Figure 4.4: The mesh of the full cup with 1104 elements

Figure 4.5: The mesh of half the cup with 1104 elements
The mesh of this model is shown in figure 4.6, the history-plot of the relative rotation is shown in figure A.5.

4.1.3 Hourglass parameter

To make an element less stiff the hourglass parameter has to be decreased. The mesh of half the cup with 4416 elements is used to decrease the hourglass parameter from 0.1 in the reference situation to 0.01, to 0.001 and to zero. The maximum relative rotation of both markers in all situations is decreased similarly by a factor 1.03.

The hourglass parameter is also increased to 0.5 in order to examine the influence of a large hourglass parameter. Here the maximum relative rotation is decreased by a factor 1.01. The results of the situation where the hourglass parameter is zero can be found in figure 4.7, for the other simulations the results can be found in figure A.6, A.7 and A.9.

![Image of mesh and figure 4.6](image)

![Image of history-plot and figure 4.7](image)
4.2 Mathematical variations

4.2.1 Material properties

The deformation of the gel is basically the result of shear. The deformation can be increased by increasing the applied force or by decreasing the shear parameters of table 3.1. The material parameters $G_0$, $G_1...G_4$, $\tau_1...\tau_4$ are decreased by a factor $10^4$. The maximum relative rotation for marker 1 is increased by a factor 1.25 with respect to the reference. For marker 2, this increase is a factor 1.07.

In order to make the material more compressible the bulk modulus can be decreased. This is done by a factor 100. The maximum relative rotation is increased by a factor 2.34 for marker 1 and a factor 3.27 for marker two.

4.2.2 Modelling of an air bubble

The cup used in the experiment has an air bubble just beneath the cover. This is a more compressible and less dense material than the gel. Therefore one element is changed to properties that describe a material that is much more compressible and less dense than the gel. A linear elastic material model is chosen with an elasticity modulus of 1000 Pa, a density of 1 kg/m$^3$ and a Poisson ratio of 0.1. These parameters have been chosen arbitrarily. The location of the air bubble is chosen directly above the nodes, selected for postprocessing. This is done to achieve the largest effect of the bubble. The maximum relative rotation of the markers is increased by a factor 1.01. To increase the influence of the air bubble, four elements are changed into air elements. These elements are highlighted in figure 4.8. Now the maximum relative rotation increases by a factor 1.01 for marker one and a factor 1.42 for marker two.

![Figure 4.8](image)

Figure 4.8: The four highlighted elements have material properties of air. The circle represents the outer node selected for postprocessing (line M-M of figure 3.2).

4.2.3 Modelling of the cover

In the reference situation the cover is modelled by restricting the nodes of the top layer to move in axial direction. However, in reality the cover is not infinitely stiff. Therefore two simulations are done where the cover is modelled by elements. In

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1. Using a fourth mode Maxwell model is possible with MADYMO. However the parameters $G_1...G_4$, $\tau_1...\tau_4$ are not returned in the reprint file. A test is done removing these parameters. The output of this simulation differs from the reference, although the differences are small. It can be concluded that MADYMO uses the parameters, but doesn't return them in the reprint file.
the first simulation, the top layer of the gel elements have been changed to perspex elements. Therefore the material properties have been changed to a linear elastic material with a Young's modulus of $2.5 \cdot 10^9$ Pa, a Poisson ratio of 0.3 and a density of $1.2 \cdot 10^3$ kg/m$^3$[5]. The maximal relative rotation increases by a factor 2.20 for marker one and a factor 3.13 for marker two.

Another way to model the cover is to add a layer of SHELL4 elements on top of the gel. These elements are given the same material properties of perspex. The elements have a thickness of 2.0 mm. The default number of integration points of two is not changed. Now the maximum relative rotation is increased by a factor 2.56 for marker one and a factor 3.48 for marker two. In contrast with the reference model, the relative rotation has only positive values for the first 30 ms, but is still oscillating at a high frequency. The relative rotation of this simulation can be found in figure 4.9.

![Figure 4.9: Cover model: one layer SHELL4](image)

### 4.3 Discussion and conclusion

In order to prevent the kind of locking that occurs in the simulation of the reference model of section 3, several changes have been made.

- Relative marker rotation was found to decrease with decreasing element size.
- The hourglass parameter was found to have no effect at all
- Decreasing the value of the parameters used in the 4th order Maxwell model to model the material behavior was found to have little effect. Decreasing the bulk modulus results in larger relative rotations, because it increases the compressibility of the gel.
- Modelling an air bubble increases the relative rotation by a small factor.
- Modelling a cover using elements with material properties of perspex has the largest influence. This increases the maximum relative rotation by a factor 2.2-3.5. Still this is a factor 4 below the maximum rotation of the markers in the experiment.

However none of the changes made resulted in a response that comes close to the experimental response. The SOLID1 element is apparently not useful to describe
the filled cup if a cover is used. The only other 3D element MADYMO has available for modelling solid materials is a SOLID8 element. This element can not be used for this type of model, as concluded by Bressers[2].
Chapter 5

Conclusions and recommendations

In the experiment described in chapter 2 a cup filled with gel and covered with a plate is rotated over 2.4 rad in 38 ms. The response has the same trend as the response found by Bressers\[2\]. However the maximum relative rotation of the markers with respect to the cup is less than it was in experiments done with an open cup. This is due to the fact that the three dimensional movement found by Bressers is suppressed using a perspex cover. Also the position of the markers is different. Bressers placed the markers on top of the gel, while in the covered cup, the markers are placed at half the height.

Simulating the experiment with a FEM model using MADYMO results in a kind of locking behavior. The relative marker rotation is oscillating at a high frequency and the maximum is decreased by a factor 13-17.

In order to find the reason for the locking behavior several parameters are varied in chapter 4. Changing the density of the mesh and changing the hourglass parameter essentially did not change the response. The largest effect is obtained by different modelling of the cover plate. In the reference situation the cover is modelled by suppressing the top nodes to move in any direction. By using elements having the material properties of perspex, the relative rotation increases by a factor 2.2-3.5. This is still a factor 4 below the experimental results. If all boundary conditions on the top are removed, including a cover, the response has the same trend as the experiment with the open cup has.

Using the elements MADYMO has available it is not possible to model a covered cup. The combination of a highly incompressible material model in combination with several boundary conditions results in a response comparable with locking of the elements. Since it is not possible to model a covered cup, modelling brains in a closed skull might also cause problems.
Bibliography


Appendix A

Results of the parametric study

The history of the relative marker rotation with respect to the cup of the simulations that are described in chapter 4 are shown here. The two solid lines simulate two of the markers in the gel, the dashed line is the rotation that the cup experiences multiplied by 0.1. The marker rotation as found in the experiment is shown in figure 2.3. The same scale is chosen as used in the experiment for easy comparing.

Figure A.1: Reference simulation
Figure A.2: *No boundary conditions set on the midplane, i.e. open cup with half the height*

Figure A.3: *Full cup with 1104 elements*

Figure A.4: *Half cup with 1104 elements*
Figure A.5: Full cup with 70656 elements

Figure A.6: Hourglass parameter 0.01

Figure A.7: Hourglass parameter 0.001
Figure A.8: Hourglass parameter zero

Figure A.9: Hourglass parameter 0.5

Figure A.10: Parameters of the 4th order Maxwell model divided by 10
Figure A.11: Bulk modulus divided by 100

Figure A.12: One air element

Figure A.13: Four air elements
Figure A.14: Cover model: one layer SOLID1

Figure A.15: Cover model: one layer SHELL4