SIMULATION MODEL OF AN ICE HOCKEY STICK

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ABSTRACT

Professional ice hockey players today use hockey sticks built with carbon fibre composites. This material type has large possibilities to be tailored in order to enhance the performance of the stick, but still it is primarily used for its high strength and light weight compared to the classic wooden stick.

A simulation model has therefore been developed to help the designers of the next generation of hockey sticks with visualization and evaluation. New material combinations, new stacking sequences and/or geometry changes will affect the performance of the stick. The simulation model can be used both for static and dynamic simulations, allowing for comparison of different designs without the cost of manufacturing prototypes.

The presented work is focused on how to model the performance of the reference stick, and how well the model corresponds to the reference stick. A new lay-up sequence is presented in order to show how the simulation model can be used for evaluation. The proposed new design shows an increase in the puck velocity and accuracy by decreasing the loading time of the stick with 15%.

1. INTRODUCTION

The hockey equipment manufacturer Salming Sports want to strengthen their position on the market by leading the technical development of hockey sticks. Due to the long lead times in using trail and error methods to build up experience and develop new sticks, they were interested in the possibilities of using the finite element method to evaluate concepts before spending the time and cost of manufacturing prototypes. The scope of work consisted of constructing a reference model by experiments and use it for comparison to evaluate new ideas of material and geometry. The boundary conditions, loads, material lay-up etc. is not presented due to costumer request.

2. EXPERIMENTS

A static tests were conducted. The results were used to adjust the material parameters to have good correlation between the reference model and the reference stick. The conducted test was simply supported three point bending, see Figure 1, with position of first support and load force in Table 1, Loadcase 1,2,5 and 6 in shot direction and 3,4,7 and 8 in perpendicular direction of the shaft. The load used was 70.5 N. .

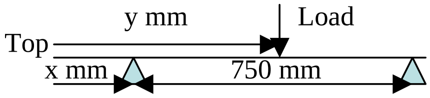

Figure 1 Three point bending

Table 1 Positions of load

Loadcase	1	2	3	*4*	5	6	7	*8*
X	50	470	50	470	50	470	50	470
Y	425	840	455	880	465	885	885	890

Simple boundary conditions were used in the reference test in order to achieve good correlations to the reference FE-model.

The eigenfrequencies of the stick were evaluated by constructing a frequency response function (FRF). This gives a plot were each peak indicates an eigenfrequency. Two different setups were used in the test and averages of the two were calculated. The setup of the experiment can be seen in Figure 2 below. The stick is suspended by bungee cords attached at node points for the stick's lowest flexible eigenmodes simply found by the feel in the finger during excitation. The arrows and crosses indicate positions and directions of the accelerometers. The stick is excited in line with accelerometer 1 in the first test and 4 in the second.

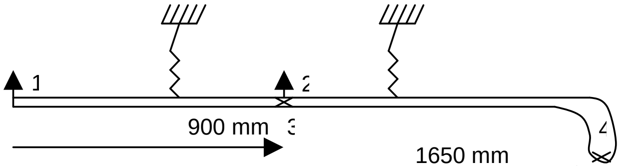

Figure 2 **Setup of FRF experiment**

The dynamic properties of the stick were measured by using a high speed video camera operating at 1000 Hz to capture to motion of the slap shot by a professional player. The parameter evaluated was the coordinates of a few points on the shaft relative a reference point. This makes it possible to evaluate the velocity and the shape of the shaft and used to set up a dynamic simulation model.

3. FINITE ELEMENT REFERENCE MODEL

The reference model has been built up for Abaqus/Standard and Abaqus/Explicit by shell elements for the composite parts of the stick and solid elements for the epoxy core of the blade. Target element size in the FE-model was 4 mm.

The shell elements were assigned orientations to which the composite lay up have been assigned. By using composite definitions in the FE-model it is possible to adjust the properties, angles and stacking order of the composite to tailor the performance of the model.

From the experiment that was carried out and using a specification of the material lay up from the manufacturer, the Young's modulus of the plies were adjusted in the static FE-model model in order to get good correlation between the model and the test.

The three point bending was used to evaluate if the Young's modulus of the laminate were satisfying, since the boundary conditions and loads are simple to simulate in the reference FE-model. The positions of the constraints and force were according to the test and the displacement was measured in the direction of the force.

With the properties of the laminate determined in the static simulations, the dynamic model is built up. The velocity and translation of the stick that could be extracted from the high speed film were used to adjust the rotation center and the angles of the dynamic model. In the dynamic simulation model motion was controlled by a prescribed motion of 50^o about the rotation center applied by amplitude function smooth step. The setup of the dynamic model is seen in Figure 3 below.

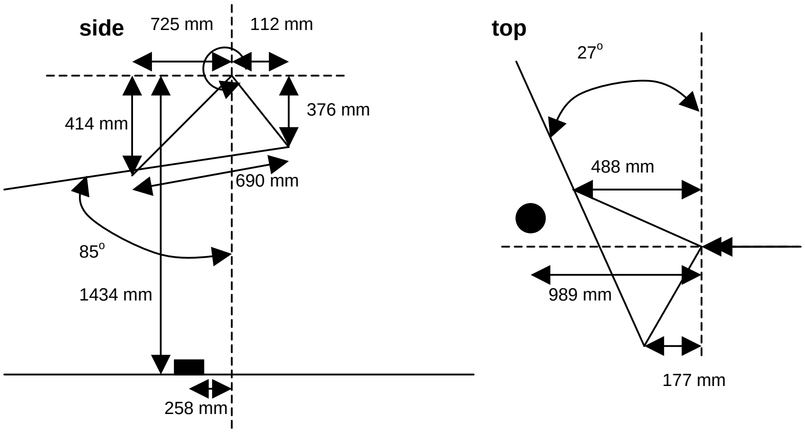

Figure 3 **Setup of dynamic FE-model**

The material lay up and properties of the plies is seen in Table 2 and Table 3 below. The angle is measured relative the longitudinal axis of the shaft.

Table 2 **Material lay up**

ply	1	2	3	4	5	6	7
t mm	0.181	0.126	0.126	0.111	0.191	0.126	0.111
angle	45	90	0	45	90	0	45
type	weave	weave	UD	weave	Weave	UD	weave
ply	8	9	10	11	12	13	14
t mm	0.126	0.306	0.126	0.111	0.126	0.111	0.153
angle	0	45	0	45	0	45	0
type	UD	weave	UD	weave	UD	weave	UD

Table 3 **Properties of the plies**

Property	*weave*	*UD*
E_1 (MPa)	60000	100000
E_2 (MPa)	60000	6000
v_{12}	0.05	0.303
G_{12} (MPa)	4500	3500
G_{13} (MPa)	3000	3000
G_{23} (MPa)	3000	3000

4. EXPERIMENTAL RESULTS

4.1 Static tests

The values from the tests are considered to be rough due to the visual read of the dial indicator and rulers used for measuring the displacement and the position of the supports and load. The results are however considered to be good when the error is about 20 % and enough to suite its purpose to build up a reference model.

The three point bending test is considered the most reliable to use as guideline to determine the Young’s modulus, since it has a simple supports and load that easily can be recreated in the simulation. The results are seen in Table 9 below.

4.2 Eigenfrequency

The eigenfrequencies have been evaluated through a plot of the frequency response function, FRF, against the frequency. Each frequency corresponding to a peak, as seen in Figure 4, has been sampled and a total average has been calculated.

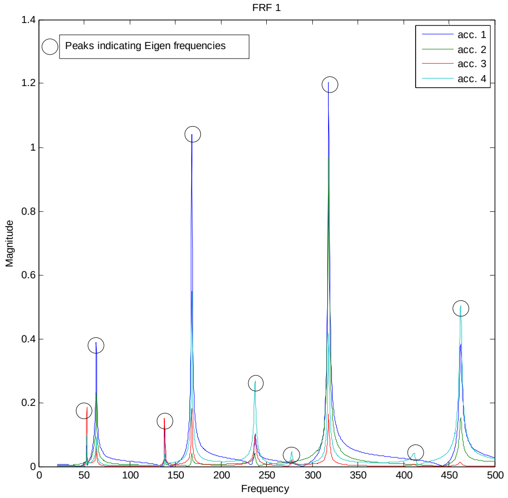

Figure 4 **Frequency response functions from the first measurement.**

The evaluated range of frequencies was 20-500 Hz. From the two tests a total average for each frequency was calculated [1], giving 9 eigenfrequencies, seen in Table 10 below, in the measured range. The lowest frequency in the model is 53 Hz.

4.3 High speed film

The results from high speed films are the most important parameters in order to build a good simulation model. The results from the high speed film are used for adjusting the position of the rotation centre, the angles of the stick and the amplitude curve used for applying the displacement.

The velocities used to evaluate the reference model are captured at the beginning, when the blade comes into contact with the surface, the lowest velocity and the velocity at the end of the contact between puck and blade. The velocities is presented in Table 4 below, and their positions from the top of the shaft in Table 5

Table 4 **Velocities used for evaluation**

Velocity	*Point 1 (m/s)*	*Point 2 (m/s)*	*Point 3 (m/s)*
v_{init}	21.02	20.02	18.03
v_{min}	11.05	10.20	7.62
v_{end}	22.20	18.25	14.32

Table 5 **Position of evaluated points**

Point	1	2	3
Coordinate in local x direction (mm)	-1404	-1225	-1006

The total contact time between puck and blade for a professional player is 38±9 ms, puck velocity 33±5 m/s and puck acceleration 63.8±9.9 g [2].

To compare the simulation model's motion with the real stick a few displacements during the film was evaluated. These are presented in Table 6 as the difference in the respective direction.

Table 6 **Displacement of measured points during the high speed film**

Displacement	*Point 1 (mm)*	*Point 2 (mm)*	*Point 3 (mm)*
Shot direction	427	382	324
Gravitation direction	20	37	52

5. FE model results

5.1 Static model evaluation

The primarily measurements used to adjust the material properties were the three point bending. This is due to the simple boundary conditions that could be applied. In Figure 5 below the static FE-model is seen. Positions of boundary conditions and load are according to the experiment in Figure 1.

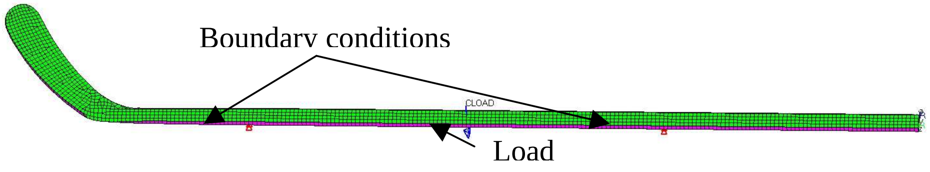

Figure 5 **Static FE-model**

The displacement in Table 9 below is from the simulation of the adjusted Young’s modulus.

5.2 Eigenfrequency

The eigenfrequencies in the range of 20-500 Hz of the simulation model were extracted by the use of Lanczos eigensolver. The lowest eigenfrequency of the reference model was 53 Hz. The additional frequencies in the range are presented in Table 10 below.

5.3 Dynamic model evaluation

The first parameter evaluated when creating the simulation model were the velocity of the shaft. In Table 7 the velocities at three different points corresponding to the ones evaluated in the high speed film are presented.

Table 7 **Velocities of evaluated nodes**

Velocity	*N38 (m/s)*	*N1690 (m/s)*	*N1061 (m/s)*
v_{init}	19.1	16.8	14.2
v_{min}	9.4	5.9	8.4
v_{end}	19.1	11.5	11.3

The second evaluated parameter was the displacement of shaft. The displacement of the same points as in the previous case during the evaluated period is presented in Table 8.

Table 8 **Displacement of the evaluated nodes**

Displacement	N 38 (mm)	N 1690 (mm)	N 1061 (mm)
Shot direction	350	320	283
Gravitation direction	13	27	43

The maximum velocity of the slap shot was 27.3 m/s. The contact time between the blade and the puck was the time during which the puck accelerates. The total contact time in the simulation was 31.3 ms. The average acceleration between the first contact to maximum velocity was 55.6 g.

The reaction forces in the constraints can be used to compare how large force that is needed to push the stick through the slap shot with different sticks. The maximum total force needed in the reference model was 5034 N. The time until the peak of the force is reached can indicate how long time it takes to store up the maximum energy in the stick. The time in the simulation model was 169 ms.

6. COMPARISON BETWEEN EXPERIMENTS AND REFERENCE MODEL

6.1 Static evaluation

The static test was used to evaluate the Young's modulus of the plies. The lay up of the plies were specified and the simulations have to consider bending in two different directions of the shaft. Therefore the process of finding good correlation between the test and the reference model become iterative. The error in Table 9 is considered to be good regarding the purpose of the model to be used to compare new geometries and material designs.

Table 9 Error from the three points bending

Load case	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Max. simulated disp.	1.32	1.34	0.65	0.66	1.30	1.32	0.64	0.65
Max. measured disp.	1.52	1.48	0.78	0.70	1.49	1.44	0.85	0.75
Error %	12.9	9.7	16.4	6.1	12.6	8.2	24.5	13.0

6.2 Eigenfrequency

The eigenfrequency gives an indication of the stiffness of the stick. In Table 10 is the comparison between the measured stick's and the simulation model's eigenfrequencies presented. Regarding the fact that the parameters are estimated from tests, the error must be considered as low. These results indicate that the overall stiffness of the simulation model is close to the stiffness of the real stick.

Table 10 Comparison of the eigenfrequencies of the stick and the simulation model

Eigenfrequency	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Average(Hz) Measured	53.4	63.2	140.4	166.9	235.1	279.9	317.8	409.9	451.0
Frequency (Hz) Simulated	56.2	65.6	149.9	174.2	218.9	278.2	328.5	399.0	417.5
Error %	5.3	3.8	6.8	4.3	6.9	0.6	3.4	2.6	7.4

6.3 Dynamic model

When comparing the results from the dynamic simulation model and the high speed film, the errors from all previous presented results must be taken into account. The model was built up using approximated values from start to finish. The geometry was scanned, the material properties were created by rough measurements and estimations and the boundary conditions are an approximation to the motion of the player.

In Table 11 the error shows that during the evaluated time of the slap shot the stick moves slower than in reality.

Table 11 Error in displacement between simulation and high speed film

Displacement	*N38 - Point 1*	*N1690 - Point 2*	*N1061 - Point3*
Error	18.0 %	16.2 %	12.7 %

The velocities of the simulation model were overall lower than those of the high speed film. In Table 12 it is clearly shown that the difference was large at a few points. This can though relate to that the high speed film did not capture the velocities at the same instances as the simulation model. It can also relate to the fact that the simulation model bounces more against the surface than in reality since the boundary conditions are rigid and do not have the dynamic damping effect as the players arms and body.

Table 12 Error of velocity between simulation model and high speed film

Velocity	*N38 - Point 1*	*N1690 - Point 2*	*N1061 - Point3*
v_{init}	9.1 %	16.1 %	21.2 %
v_{min}	14.9 %	42.2 %	10.2 %
v_{end}	14.0 %	37.0 %	21.1 %

The velocity, acceleration and contact time of the puck in the reference model can be compared with the values in Chapter 5.3. This shows that both the contact time and the maximum velocity in the simulation was within the limits for a professional player. The acceleration from the first contact between the puck and the blade to maximum velocity was also in the range.

7. A NEW MATERIAL DESIGN

In order to evaluate if the simulation model can be used as intended, a new material design was created. This could be made very quickly since only material parameters had to be adjusted and the mesh from the reference stick could be kept.

The idea was to create a material design that lowers the point were the primary bending of the shaft occurs. This is called kick back point and the objective was to attain as short loading and release time of the shaft as possible in order to make the slap shot more rapid. This can be made by reducing the bending stiffness of the lower part of the shaft. An increase of the torsion stiffness is also desirable in order to make the shot more accurate since the blade will face the shot direction better and not allow the puck to roll of the tip of the blade.

The stick was divided into three sections as seen in Figure 6. The upper and the lower part had the same properties as the reference stick, while the middle section had a lowered amount of fibers in the longitudinal direction and an increase in a 45^o angle of this direction.

Figure 6 Sections of the new stick.

The static comparison of the three points bending is presented in Table 13. There are only the two load cases on the lower part of the stick evaluated since it was the only part where the difference in lay up had any effect. The new stick shows an approximately 3 % less stiff performance than the reference stick, which was intended with the new material.

Table 13 **Comparison of the three points bending**

Load case	*2*	*4*
Difference %	2.9	3.3

In order to compare the torsion stiffness a new load case was created. The load was applied as a torque on the shaft and the displacement is measured for a node at the tip of the blade. The shaft is clamped and a torque is applied as in Figure 7 below.

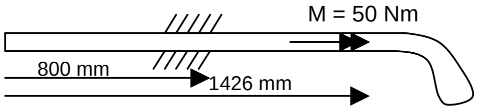

Figure 7 **New load case**

As seen in Table 14 below, the new stick is 6.1 % stiffer in torsion than the reference stick.

Table 14 **Displacement of node at tip of blade**

Evaluated node	*Disp. new stick [mm]*	*Disp. ref. stick [mm]*	*Difference*
N 4207	32.2	34.3	6.1 %

The new puck velocity was 27.7 m/s and that is an increase with 1.5 % compared to the reference stick. The contact time between the puck and the blade was the same as with the reference stick. This gives approximately the same increase of the acceleration as for the velocity.

The maximum force needed to push the stick through the slap shot was only 2780 N at 144 ms of the simulation time. This is 15 % earlier than the reference stick and the characteristic of the force curve is somewhat different. The peak force was reached earlier but withheld for some time, as seen in Figure 8, while the force for reference stick continuously increases until it reaches the maximum and then decreases significantly. This is interpreted as the time before the player could release the shot with the same, or better, result than with the reference stick.

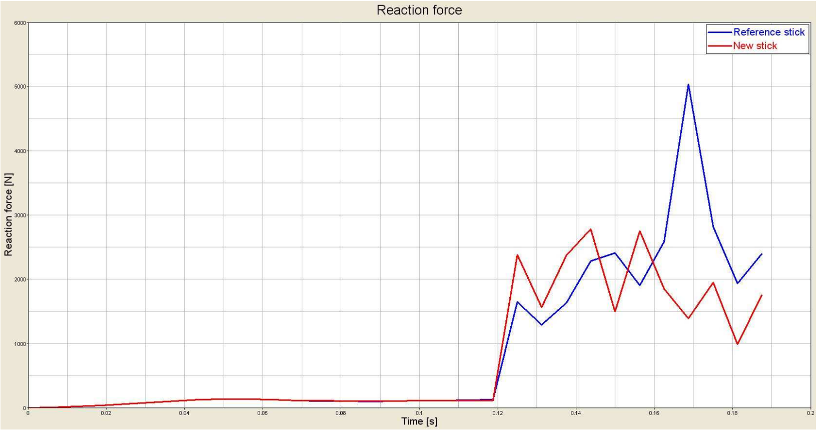

Figure 8 **Reaction force in reference and new stick.**

The peak force is 45 % less with the new stick. This can be considered a bit unrealistic but the trend is still that the peak occurs earlier which makes the shot with the new stick more rapid.

Another thing that could be considered in the dynamic model was the accuracy of the shot. To evaluate this subjective parameter the drift in the transverse direction is compared. The new stick had a 16 % less drift, seen in Figure 9.

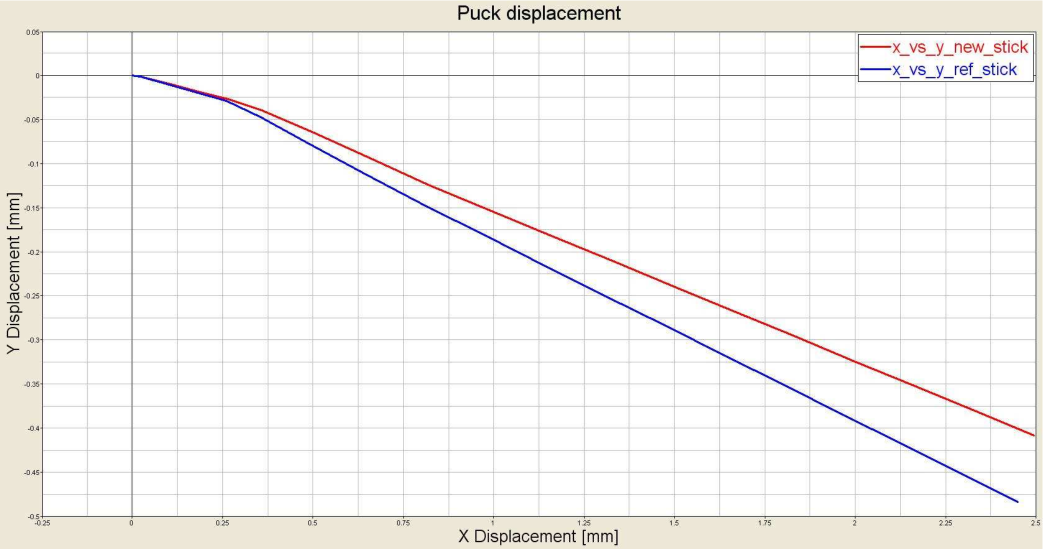

Figure 9 **Drift of puck in simulation**

The last comparison made for the new stick was the kick back point. In Figure 10 it is clearly seen that the lower part of the new stick was more bent than the reference stick. For the upper part it is not that clear, but the new stick is straighter than the reference stick. This is the result of the new material design with a less stiff middle section and is considered as a lowered kick back point.

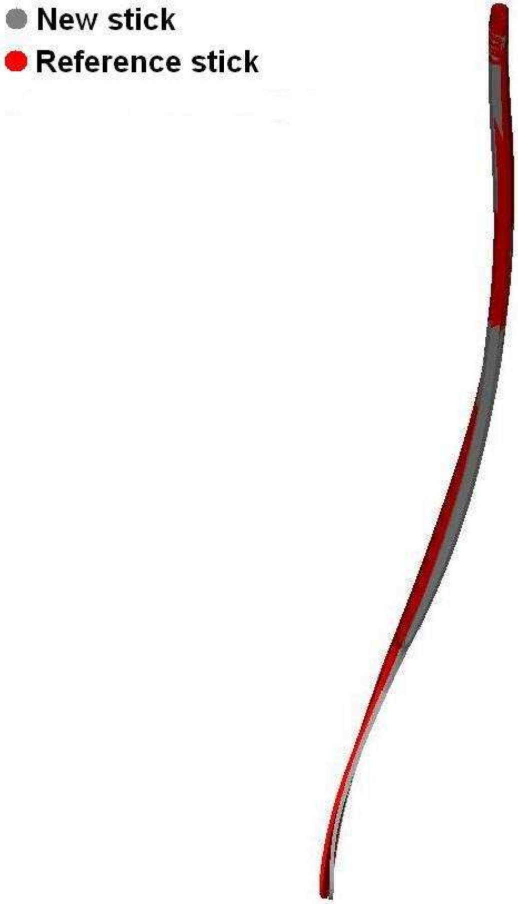

Figure 10 **Shape of the shaft during the slap shot.**

7. CONCLUSIONS

The work was concentrated on developing a simulation model that can be used as a tool in the development of new ice hockey sticks. The main objective were not to get an exact recreation of the performance, but a model that can give a prediction of how a new design of geometry or material could perform. The comparison can be made with a reference stick according to the load cases described and the outcome can be in terms like, a stiffer shaft in bending, in torsion, higher puck velocity etc. Therefore it has not been necessary to have an absolute correspondence between the simulations and the conducted tests.

During the evaluation of the simulation model some large errors have been presented. These should be taken into consideration when using the model to simulate new materials and designs. Both the static and the dynamic model can give results that show better performance than the reference stick, but can relate to the boundary conditions used in the models. An example can be that the static model does not take the whole sticks torsion into account, but only the lower part.

The dynamic simulation model can visualize the performance of the stick during a slap shot. After conducting the static evaluations of several designs, a few of these that perform desirably can be further evaluated with the dynamic model. In the dynamic simulation a rough prediction of how the new stick will perform during a slap shot can be made and those with the best performance can be taken further to build prototypes. Since the model is a simplification of the reality and dynamic effects from the player might cause differences in the results from the simulations it is always the players opinion that in the end will decide which stick to produce, but the simulations can help the developers to try a lot of different ideas before to cost and time of making prototypes is necessary. Another benefit with doing the simulations is that they faster can build up knowledge of how different designs of geometries and materials will affect the performance and take a leading position in the technical development of ice hockey sticks.

The new stick presented in the thesis is only one idea of how to adjust the material design in order to get a desired performance, but it emphasizes the possibilities with using simulations. Technical advancements can be achieved by the use of this virtual tool.

ACKNOWLEDGEMENTS

The work presented in this paper has been conducted at Semcon Caran AB for their costumer Salming Sports as part of a master thesis by Per Orestig for Chalmers University of Technology.

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