How to win the kayak Olympics

Or how to design and produce an innovative flatwater kayak paddle...

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Introduction

A kayak is a very ancient way of riding in the water; human-powered, it is propelled by means of a double blade paddle. It is used nowadays to fish, to travel, or to compete at the Olympics. It is the 1,000 meters flat-water race that led this project, and particularly its improvement for Steven Ferguson, the actual New-Zealand kayak champion. This report presents the different parts that have been investigated to improve the paddle efficiency in the water, and therefore the speed of a kayak athlete on the water.

Kayaks are 4,000 years old, and kept since the basic shapes of their hull and paddle. It is only in 1987 that a Norwegian team developed an improved paddle, which is still used nowadays. Every paddle currently available on the market follow this design. Based on fashions and on the success of athletes, they were unable to suggest any major improvement since. This project suggests a way of significantly improve the performance of an athlete in a flat-water kayaking competition.

1 - Recording the motion

The motion of the paddle while racing, and the one of the athlete’s body, are very complex. Previous studies showed that these motions vary from a champion to the other. Some other examined the body’s motion and the possible injuries caused by the repetition of this motion. This project focused on a series of recorded data, comparing paces and athletes. Different parameters and global trends have been deduced, from which a design could be extracted.

2 - Designing a shape

The suggested design modifies radically the previous designs drag-based, and even changes from the latest one known as the Norwegian blade. The different parameters from the motion capture have been compiled, in order to produce the theoretical most performant blade. A simplified analysis has been performed, which could still be improved using more advanced hydrodynamical and mechanical notions, which are discussed here.

3 - Making it strong

Such a design is nowadays available thanks to the development of composite materials. Using a sandwich structure with carbon fibers skins allows to be light and strong. The properties of the materials used have been studied and compared to be resistant to that particular motion, the one of the blade during a stroke in the water. Subjected to consequent stresses, the shaft has been locally reinforced.

4 - Building a prototype

A sandwich structure leads to a relatively complex process. To produce the paddle following the computed design with accuracy, and to lay up the layers as thought in the structural part, is not straight forward. A multiple steps process has been developed and improved. The core is CNC machined, the skins hand laid-up and reinforced with a vacuum. The final blade displays the designed geometry with a sufficient accuracy.

5 - Trying it

Testing and feedbacks are essential in a qualitative job. The feeling of the athlete using the improved paddle would be completed by recording the motion of the water around the blade. Since each blade would give different results, the feedbacks would finally be compiled to start over the whole process. They allow to rethink the design according to the new motion.

This project has been studying the previous parts, and their implications. The following scheme describes the design loop:

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Recording the motion ----> Designing a shape ----> Making it strong ----> Building a prototype ----> Trying it
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Following this loop scheme a few times would give a very effective paddle, the modifications being smaller and smaller on each steps. One full round over this loop has been performed in this project. Improvements could be the basis of new projects; they will be discussed in the different parts of this report.
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CHAPTER 1

Recording and analyzing the motion
How to record and to analyze a motion

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Introduction

The motion of the paddle while racing, and the one of the athlete’s body, are very complex. Previous studies showed that these motions vary from a champion to the other. Some other examined the body’s motion and the possible injuries caused by the repetition of this motion. This project focused on a series of recorded data, comparing paces and athletes. Different parameters and global trends have been deduced, from which a design could be extracted.

1.1 Motion capture in sports

For each sport, coaches have different ways to improve the gestures of an athlete. From the video shot, they can easily point out which part of the body differs from the known as a perfect motion. For complex motions, shooting from different angles, or superposing different shots can be very useful. This requires a motion capture system.

1.1.1 Need of the motion capture

In kayaking, the choice of a blade for competing is mostly based on a feeling. This project managed to find a scientific approach to evaluate the performance of a blade. This allows the comparison between blades, and might improve the feeling of the athlete.

The generic stroke has been taken as a reference to start the design loop. Since the motion is complex, an accurate way of recording the stroke would give useful data. Decomposing the motion would allow to understand the motion of the water around the blade.

Video shots from Steven Ferguson paddling gave basic informations about angles and distances. But recording accurate data on water is a costly exercise. It requires the use of wifi or bluetooth, coupled to accelerometers and some powerful data analysis softwares. Previous work has been performed [1], which looked at a few basic angles only. A more complete system is used, which allows to understand in details the complexity of the stroke and its implication on the performance.

Figure 1.1: Detail of one of the eight Vicon cameras.
1.1.2 A video system called Vicon

Vicon is a capturing system mostly used for cinematic scenes, to record the motion of a character. The CACM has access to this system through the sport sciences department of the University of Auckland, which uses it to record athletes' motion. It uses a series of cameras with very accurate resolution, as shown in 1.1.

The University of Auckland disposes of eight cameras. They are fixed in a room around a testing area, as shown in 1.2. Some markers are stuck onto the shaft, which are grey solid balls. The system initializes to recognize the cameras from each other and to calibrate the distances. It is then ready to track and record the motion of the markers.

![Figure 1.2: Motion capture process.](image)

As a start, the motion of a paddle is recorded with the athlete sitting on a chair. This simple experiment allowed to develop the data analysis. A series of experiment is then performed on an ergometer, to be closer from the real motion.

Two different athletes are being recorded paddling at four different paces: 40.0 strokes/min, 50.0 strokes/min, 60.0 strokes/min and 70.0 strokes/min. The pace was defined before the tests, and given by a metronome. More than 50 strokes were recorded and then averaged. The series shows the common trend of the blade motion, and allows to compare and explain the variations.

The design will focus on a particular motion, corresponding to a 1000 meters race. A few first strokes will allow the athlete to accelerate, the remaining one to keep its speed. Since the acceleration is short on a long race, most of the strokes will be following a steady repeated motion, around 70.0 strokes/min. This particular motion is the one which has been extracted in this project.

1.2 Comparing paces and athletes

A previous study [6] is giving a hint about the successful blade path. Higher stroke rate is preferable to a longer stroke length. Also, entering the blade further forward and closer from the hull centerline seems to be more efficient.

1.2.1 Differences between blades

Left and right blades have a similar global motion in the water, but seem to follow two different paths. No one got a symmetrical body, the motion is emphasized on one side and less on the other. This might be less true in water, when the tilt of the shaft may lower the resistance of the blade. The body also balances the hull and impacts on the surface of the blade which is immerged.

To produce a perfect paddle for a given athlete, it is probable that both blades would be different. This would be non-natural for the athlete who would not be used to it. For this reason, and to simplify the study, both blades are analyzed in the same plan and then averaged. The non-symmetrical effect is shown in 1.9.

1.2.2 Differences between paces

The study allowed to look at four different paces: 40.0 strokes/min, 50.0 strokes/min, 60.0 strokes/min and 70.0 strokes/min. The latter is used during the 1000
meters race, it is therefore the one of interest. Slower paces actually show a cleaner stroke, with less variance in the motion. At higher pace, the body needs to push harder and has less control and accuracy.

The averaged motions for the different paces are very similar, and differ only slightly in the length of the stroke. An average over more than 100 strokes is smooth enough to be used. The 70.0 strokes/min has been preferred for the study since it reflects the real case, and since it does not differ too much from slower motions.

1.2.3 Differences between athletes

Two different athletes were tested and recorded. The one known as "Athlete 1" has been training regularly and competing. She is shorter and has a preference for her right hand. The other one, known as "Athlete 2", was a kayak amateur, taller and having a wider shoulder span. He was also left handed. All these parameters have an influence on the strokes, it is therefore hard to give conclusions at this stage.

A previous study [9] has been investigating the major difference between different athletes. With the help of a model, it showed that the paddle velocity relative to the boat, in other words the strength of the athlete, is the key parameter. The following parameters were also having an influence: upper body motion, mass of the athlete, mass of the boat, stroke rate.

1.2.4 Motion improvements

Collecting data gives informations about the motion of the paddle; it can therefore help the coach to lead the athlete towards a perfect motion. This perfect motion will be driven by the design of the blade.

Figure 1.3 shows the efficiency in time of each stroke, and the loss in comparison, when the paddle is not in contact with the water. The two different athletes efficiency are displayed, for the four paces. The perfect motion tends to decrease the loss time, as shown in white.

The figure shows that Athlete 1 is losing some water contact time at lower pace, and is steady at higher paces. She is also more symmetrical than Athlete 2, who is steady through different paces, but who uses is preferred hand more. This would make the hull heel, and therefore drag more, which should be avoided.

1.3 Usefulness of the captures

It has been shown that Athlete 1 has a more symmetrical stroke. Furthermore, no data were recorded for Athlete 2 at the highest pace. This will be the start of the design, which should minimize the drag but maximize the thrust. The result can then be extrapolated to the real motion of our Olympian during a 1000 meters race.

1.3.1 Averaging on 1000 meters

The motion of Athlete 1 at very high pace has been averaged over more than 100 strokes, to give an estimation of the real motion. A 3 dimensional movie has been performed under MatLab, to be able to visualize the paddle motion 1.4. Different views are also available to help understand this motion in space, shown in 1.7, 1.8 and 1.9

In these figures, the purple arrows shows the direction of the boat. The light blue grid represents the height at which the water would be. Since the floor was appearing the motion capture, the position of the hips of the athlete could be measured. The elevation of the same point has been measured in the water to estimate the water level.

The red dots and lines show the path of the tip of the blade. The green dots and lines display the geometrical centre of the shaft. It moves with a significant amplitude, of 300 mm, as shown in 1.9. The paddle is shown in black to help the visualization. Finally, the motion of the water around the center of the blade is given in blue. It gives the angle of attack and its angle of application on the blade. The magnitude gives the velocity of the blade relative to the water, as a first derivative of the displacement.
The above figures show the water displacement at the following times, starting at the entry in the water: 0 ms, 80 ms, 160 ms, 240 ms, 320 ms. The blade exits at 380 ms.
How to win the kayak Olympics

The above figures show the water displacement at the following times, starting at the entry in the water: 0 ms, 80 ms, 160 ms, 240 ms, 320 ms. The blade exits at 380 ms.
Another code has been developed to compute the angle of attack. Figure 1.5 gives the vector velocity of the water relative to the blade, shown in blue. The light blue arrow gives the direction of the boat and the black curves the blade itself. The motion is not steady and obviously needs to be decomposed for a better understanding. Figure 1.6 shows this decomposition of the vector velocity in the referential of the blade.

An optimization could be extracted from the values related to this figure. Each step would give a velocity and an angle of attack along a certain angle of application on the blade. Each section of the blade parallel to this angle of application could have a certain shape, for which lift and drag could be computed. The optimization would try to get the maximum lift and the minimum drag on the sum of these steps.

1.3.2 Understanding of the motion

Finally, since the motion capture results were not available at the start of the study, a simpler model has been extracted for the design. From the literature and from the professionals experience and feelings, it seems that the major component of the stroke is the sideways motion, i.e. the middle picture of figure 1.6. From this motion, a low drag and a high lift give the highest thrust.

As per the figure, three distinct phases of the stroke can be named, clearly illustrated in figure 1.7. The entry in the water, from when the contact with the water is made, until the full blade is immersed. The pull-out phase, during which the athlete pushes the blade away from the kayak, creating some thrust by lifting. The exit of the water, from when the blade goes more to the back than sideways, until it clears the water.

The first phase seems relatively complex, and has been voluntarily forgotten in this study. Its study would probably give more comfort to the user, and allow him to start catching the water earlier. As explained above, the pull-out phase is giving the thrust, and is the main aspect of the study. As the motion is almost steady during this phase, an angle of attack has been computed to be 9.4 degrees. The improvements for the last phase are discussed in the next part of this report.

Conclusion

The motion of the blade in the water highly depends on the technique and on the feeling of the athlete, and differs depending on the blade shape. A motion capture allowed to draw a global trend, by analyzing a motion on two different athletes and at four different paces.

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Chapter 2

Imagining and designing the shape
How to imagine and to design a shape

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Introduction

The suggested design modifies radically the previous designs drag-based, and even changes from the latest one known as the Norwegian blade. The different parameters from the motion capture have been compiled, in order to produce the theoretical most performant blade. A simplified analysis has been performed, which could still be improved using more advanced hydrodynamical and mechanical notions, which are discussed here.

2.1 Different existing designs

Drawing and building paddles is a very old fact. All kind of paddles exist, from the rowing oars to the propellers. Some are simply using the drag in the water, some the lift.

Some others, like kayak paddles, are a subtle combination of both, and are therefore tricky to design. Following the previous motion capture study, this part presents a way to design an efficient blade.

2.1.1 Comparisons of plates and drag paddles

Everything started with a flat plate which would give some thrust if one drags it in the water. In this case, the thrust comes only from the drag. Most of the energy spend would go towards this drag, but some would be lost in curls and vortices [11].

Stand-up paddle boards paddles, Greenland kayak paddles [3] and rowing oars developed a curved shape to minimize this losses. But their main action is still drag-based, and will remain. The global motion of the paddle can not be changed in such a way they could create lift.

2.1.2 Improvement : the norwegian paddle

A major improvement in the kayak blades came from a Norwegian team in a Swedish university. It is commonly known as the norwegian blade. A sideway motion is introduced to get some thrust from the lift of the blade and minimize the drag.

This original design allowed new performances and got quickly adopted by the kayak champions. This design is still mainly used today.

2.1.3 Possible improvements

The Norwegian blade was design at a time when composite structures where very new, and moulding costly. The shape of the blade had to be worked out to be a shell, with a specific thickness. This limiting parameter still allowed the Norwegian team to develop a new design, based on airfoil sections.

But a simple idea came up, which changed the design perspective and allowed for a possible improvement. The shell has an extrados which follows smoothly an ideal airfoil section. The empty intrados is source of
drag, with the apparition of vortices during the pull-out phase, and with a long spray of water which sticks to the blade during the exit of the water.

The main idea of being efficient is to produce thrust with the least energy. In other words, this comes to propel itself with the water remaining still. Then, all the muscular effort is going into the thrust, and the losses are minimized. A study [2] has been completed to compute the thrust of a paddle, and to estimate the speed of the boat.

2.2 Blade efficiency

From a given design and size, the project has been led towards the creation of a new shape. A prototype had been quickly built by Ian Ferguson to develop an idea. The reference paddle shape and this new shape have been analyzed and modified playing on a few parameters.

2.2.1 Wetted area and aspect ratio

Some studies [10] have been performed about the changes in aspect ratio and in area. The area is obviously directly related to the strength of the athlete. Different surface areas have been tried on different athletes, and their performances recorded. A relation between the weight and the size of the athlete, and between the blade surface has been drawn. It allows to choose a paddle for any athlete, which would be the most efficient.

The aspect ratio is then changed for a given surface area, and the performance of the athlete has been recorded. It shows that for a long aspect ratio, some of the blade is not submerged during the stroke, and therefore does not give any thrust. On the other hand, a short aspect ratio sees a significant portion of the shaft entering the water. Since the shaft is circular, it loses some thrust.

2.2.2 A lift and drag device

The motion capture clearly shows the blade going sideways during the pull-out phase. This has been shown in the first part. A sideways motion creates some lift for a plate, which gives the thrust. Drag is also created, which resists the athlete strength. But the ratio of lift created over the drag lost is higher. The athlete converted into this motion will therefore be more efficient and get more thrust for the same muscular energy loss.

2.2.3 Cross-sections and NACA profiles

As mentioned above, a plate creates some lift and some drag when pulled sideways. These forces vary mostly with the angle of attack of the plate in the water. Since the lift creates the thrust and the drag is directly related to the strength of the athlete, the design should minimize the drag and maximize the lift. These forces depend on a few variables, and can be written as follow.

\[
F_{\text{Lift}} = \frac{1}{2} C_L \rho A_{\text{blade}} V_{\text{blade}}^2
\]

\[
F_{\text{Drag}} = \frac{1}{2} C_D \rho A_{\text{blade}} V_{\text{blade}}^2
\]

In these equations, \( \rho \) represent the density of the water, \( A_{\text{blade}} \) the submerged area of the blade, \( V_{\text{blade}} \) its speed relative to the water, and \( C_L \) and \( C_D \) are respectively called the lift and drag coefficients. They mainly depend on the Reynolds number and on the shape of the blade.

The aim of the project is then to optimize the ratio \( C_L/C_D \), which can be back computed from the same equations. The computation being long and complex, a shortcut has been taken for this project, which leads to an accurate result. The Reynolds number of the blade in the water is of the order of magnitude of \( 10^6 \), similar to the one of an airplane wing. A database can therefore be used to get the lift over drag ratio.

The NASA has been filling in a very complete database of foils since the beginning of the 20th century, when the first airplane were produced. They created a model to build a scaleless foil, based on four digits. For each shape they could create this way, they measured the lift and the drag created for every angle of attack, from 0 degrees to stall angle.

This model was called a NACA profile. Each section is unique and referenced through four digits. The first one gives the maximum camber as a percentage of the chord. The second digit describes the distance of the maximum camber from the leading edge. Finally, the last two digits represent the maximum thickness of the airfoil as a percentage of the chord.

A massive database is then available on the internet, which gives the previous ratio for every possible shape of a foil. A script has been written to collect these values, and a MatLab program to pick the lift to drag ratio of each foil, and to compare them.

2.2.4 About the blade’s twist

As mentioned earlier, the so called Norwegian blade is a shell. Its shape is catching a fair volume of water during the exit phase of the stroke, during which it creates
curls and a long splash of water, about 500 mm high. These water behaviors are mainly slowing the athlete’s motion, and force him to put more strength for every stroke.

The idea which launched this project was to fill in the shell, in order to avoid these losses, and to obtain cross-sections closer from the shapes of the NACA airfoils which have been computed to be more efficient. The blade becomes 3 dimensional, with a varying thickness, and the possibility to add a twist to the blade.

A significant twist had been recorded during the motion capture. The athlete seem to avoid dragging by twisting the blade in order to have the leading edge of the paddle exiting first. A twist in the blade would probably give a more fluent body motion, and avoid the current curls and splashes.

2.3 A final design

A wide choice of NACA profiles is available, and one could thing of many ways to accommodate a blade with such shapes. The final design would take the motion capture into account, this was not available at the time. A standard blade has finally been taken as a reference, and modified to be more efficient.

2.3.1 Choices and possible ameliorations

A standard Norwegian blade was available, as well as the prototype of a filled blade. Their shape has been carefully measured thanks to a 3 dimensional digit tool. This tool gives a spatial coordinate of any point that a connected pencil touches, from a reference point and axis predefined by the user. It allowed to measure cross-sections of the blade.

The measured cross-section were drawn at an angle of 28 degrees with the shaft. This specific angle is the average angle of the shaft from the vertical during the pull-out phase. Different video footages allowed to measure this angle. In other words, the cross-sections are streamlines of the water during the pull-out phase.

The standard blade and the prototype present a very similar extrados. A MatLab program has been created to compare this extrados with the one of all NACA possible profiles. The sum of the distances between the real extrados and the theoretical NACA was minimized. It concluded that both standard and prototype blades were very close from the profile called NACA 9310.

The different cross-sections are shown in 2.1. The standard blade is drawn in red, with a shell thickness of about 4mm. The solid blue line is the profile of NACA 9310. The prototyped blade is not represented on this drawing, but follows almost exactly the NACA profile. The dashed line shows the profile NACA 9314. It is the one which has been chosen, as explained below.

A MatLab program has been created, which picks up a list of similar profile. Being similar means here being a NACA profile with only a digit of difference. From this list is extracted the profile with the highest lift to drag coefficients ratio. It is chosen as being the new design, more efficient. This operation is done twice, giving NACA 9314 with NACA 9310 as an input.

It allows to stick to the imperfect prototype shape with a design that can be called more efficient. The new profile is thicker, which is discussed later. Finally, the contour of the blade is chosen to be the one of the prototype.

2.3.2 solidThinking as a CAD tool

The project evolved to a defined cross-section shape and to a defined contour at this stage. A CAD tool was then necessary to draw the 3 dimensional shape of the chosen design. solidThinking has been mostly used in this project. ProEngineering also helped cleaning the obtained shell in order to be processed, as explained in the following part.
is drawn to this end, and the leading and tailing edges of the cross-sections aligned with it. Then, a twist is created by rotating the cross-sections on their plane. The result is shown in 2.2.

Here comes the limitations of the method used and of the software. The cross-sections are produced thanks to a points cloud. The number of points used needs to be higher than 120 to obtain a smooth curve. The curves are therefore splines for which a large number of data is recorded. When trying to obtain a shell from different cross-sections, the software creates a surface on the principle of a 2 dimensional spline. The data number to treat becomes huge, and the software did not seem to accept the work.

![Figure 2.3: Full blade obtained with solidThinking.](image)

The surfaces of the extrados and the one the intrados are finally obtained. They are then joined together to create a volume. A particular care needs to be taken regarding the the tip of the blade. To simply avoid any singularity, the tip has been virtually cut. The blade misses a part which is of the order of magnitude of the accuracy of the tooling, seen in the next part. The whole volume is finally available for construction, as shown in 2.3.

### 2.3.3 Further designs to be studied

This design has been obtained without the help of the motion capture. The motion capture giving encouraging results, it could now be used to get a finer design. This would be the scope for a new project. A way to design the blade would be to find the directing motions in the water, as a combination of two rotations for example. The blade could then be designed as propeller.

The question remains to know which would be the most efficient blade for a given motion. With such a complex motion, playing on simple parameters as the surface area, the shape of the cross-sections or the twist of the blade is not enough. It opens the doors to a complete CFD study. The design loop could maybe avoid the manufacture, which is long and costly. The perfect blade for a given motion could be found. Then, testing it in situ would give some feedbacks which would change the motion. But the number of design loops would be fewer.

### Conclusion

There is a large set of choices which can be made to design the shape of the blade. The most obvious one is to respect the design loop, and to find an effective shape from a given stroke. Unfortunately, even simplifying the stroke and designing the blade to be efficient on the pull-out phase only is a challenge.

Following simple hydrodynamic forces, a series of MatLab codes enabled the evaluation of the prototype blade, and the comparison with the actual shell paddle. Adding some thickness to the blade allowed a higher lift to drag coefficients ratio according to a NACA profile database. This ratio is the good measure of the blade efficiency, as shown in this part.

Handling a CAD software to create the designed volume was also tricky. The CAD tools are generally not using points cloud to create a volume. Issues in capacity of the software, of the computer and of the singularities of the model needed to be understood and avoided. Finally, a blade was designed, which looks strangely simple and natural.

More ameliorations could be envisaged, as the use of the motion capture for the design. The hydrodynamic being more complex than the use of NACA profile, some inaccuracies would need to be avoided when using the full motion. The decomposition of the motion in simple rotations, or the use of a CFD software might be different ways around these issues.

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CHAPTER 3

Making it strong and stiff
How to make it strong and stiff enough

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Introduction

Such a design is nowadays available thanks to the development of composite materials. Using a sandwich structure with carbon fibers skins allows to be light and strong. The properties of the materials used have been studied and compared to be resistant to that particular motion, the one of the blade during a stroke in the water. Subjected to consequent stresses, the shaft has been locally reinforced.

3.1 A sandwich structure

The 3 dimensional design has been computed to give the most efficient strokes while racing. The theoretical paddle is complex, and needs to be easily processed. A simple structure has then been chosen to fit both design and process, and to match the full requirements a paddle takes.

3.1.1 A lightweight structure

Most requirements concern the design of the blade, some its manufacturing process. Another choice is more personal, and could concern the commercialization of this new great design paddles : the cost efficiency. A wing blade paddle costs around $500 nowadays. This design, with the associated structure and process which follow, would cost $200, in which half would be the shaft itself.

The NACA profiled cross-sections that have been chosen in the design part of the project were limited in width. In other words, the cross-sections are the most efficient in the limit of the volume of the paddle, which should not exceed $10^{-3}$ m$^3$. This boundary has been computed once known the density of the structural core of the paddle, and is explained below.

This project is focusing on a 1000 meters flat-water race. The usual paddles used for this race are the 'medium sizes', for the commercially available so called 'wing paddle'. These paddles weight in average 800 grams, with a 50 grams deviation depending on the manufacturer. The goal was then to produce a blade with the same wetted area - for design reasons - which was lighter.

Keeping the wetted area constant - $6.23 \cdot 10^{-1}$m$^2$ - and modifying the cross-sections give a different volume, which would be much larger in the chosen design - $8.07 \cdot 10^{-4}$ m$^3$. The buoyancy, which could be neglected in comparison to the paddle’s weight, has now to be taken into account. To have a paddle lighter than the one of reference, a lightweight structure is obviously suggested.

With a light density of the structural core, adding the weight of the layers giving its stiffness to each blade, and adding the weight of the shaft, the processed paddles weights 780 grams. Ending up with a lighter paddle than the commercially available one is obviously hard, because they use the same kind of materials and do have very thin blades, minimizing their volume.
The final blade weights the same, but got a major improvement, due to the larger volume of its blades: the buoyancy. This will push the paddle upwards when the blade is fully immersed, at a force which is the same than the weight - approximation with an error of 3.4%. Then, the paddle would be in vertical equilibrium during a major part of the stroke.

Since the shaft is the same than for the reference 'wing paddle', having a same weight will give a better balance, so a better feeling to the athlete. The extra buoyancy will help the paddle to exit the water, and will make the entry harder, which is easier to handle for the athlete. Finally, this does not change anything else on the motion of his body, since most of his strength is converted longitudinally and not vertically.

Finally, the blade needs to have evident aesthetic properties. Its appearance should not be too revolutionary, to be easily accepted by the kayak federation for the olympics, and the athlete not to be disturbed by a different looking paddle - a different color could make him lose his focus on the race. The blades should also be waterproof, since all structural cores available are delicate.

Then, a sandwich structure has been thought. Its layers are shown in figure 3.1, from the inside to the outside: light foam core, highly stiff carbon fibers, fine and smooth glass fibers. Only the tip of the blade, and the junction of the fibers, is shown. On the rest, the fibers are following the same layout.

Figure 3.1: Lightweight sandwich structure, on the tip.

The foam gives its shape to the blade. Easier to shape, it will be machined the desired way. The fibers will then be added on its surface. The carbon fibers layer will give its stiffness to the blade, and are a major structural element, as shown below. The glass fibers will give a smooth and nice aspect to the surface. Easier to sand, they will take part of the finish of the blade.

### 3.1.2 Choice of the foam core

For the previous reasons, the foam has to be light, but dense enough not to be to fragile in compression. It has to be machinable to get the desired shape, so thick structural foams as polystyrene should avoid. It also has to have a relatively high close cell structure, to avoid the resin to impregnate through the surface and to the core, which would make the blade significantly heavier.

Different foams are available on the market, with very different properties. SP - High Modulus suggests a wide range of SAN polymer based foam, which are known for their impact resistance - capacity to absorb a transversal impact without failing. These foam blocks have a very low density, bond well to epoxy resins and are highly machinable.

The Corecell™ foams are available in five different forms, with different densities and then properties. Table 3.1 references the densities, compression, shear and tensile strengths of the different available foams. HDT is the same for all, 110°C, which is above the curing temperature of epoxy resin.

<table>
<thead>
<tr>
<th>Type</th>
<th>Units</th>
<th>M60</th>
<th>M80</th>
<th>M100</th>
<th>M130</th>
<th>M200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal density</td>
<td>kg/m³</td>
<td>65</td>
<td>85</td>
<td>107.5</td>
<td>140</td>
<td>200</td>
</tr>
<tr>
<td>Compression modulus</td>
<td>MPa</td>
<td>0.55</td>
<td>1.02</td>
<td>1.55</td>
<td>2.31</td>
<td>4.40</td>
</tr>
<tr>
<td>Compression strength</td>
<td>MPa</td>
<td>31</td>
<td>52</td>
<td>76</td>
<td>111</td>
<td>210</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>MPa</td>
<td>0.68</td>
<td>1.19</td>
<td>1.45</td>
<td>1.76</td>
<td>2.495</td>
</tr>
<tr>
<td>Shear strength</td>
<td>MPa</td>
<td>20</td>
<td>44</td>
<td>41</td>
<td>56</td>
<td>98</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>MPa</td>
<td>0.81</td>
<td>1.62</td>
<td>2.11</td>
<td>2.85</td>
<td>4.29</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>44</td>
<td>72</td>
<td>109</td>
<td>176</td>
<td>334</td>
</tr>
<tr>
<td>HDT</td>
<td>°C</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Available thickness</td>
<td>mm</td>
<td>20</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3.1: Properties of the available foams.

Compress strength is only necessary to transport the paddles. Shocks on the blades would compress the blade in a higher way than during a smooth stroke in the water. Avoiding making holes in the structure during the transport could then be an issue in the choice of the foam. Simple tests have been performed on M80 and
M200 foams, covered with two layers of fibers. None of these tests failed.

All M-foams can be used according to their compression strength. Two layers covering the structure reinforce the blade enough and avoid creating holes. Shear and tensile strength of the blade will be mostly ensured by the reinforcement fibers. Density of the foam will then be the interesting property, since the blade need to be the lightest possible.

Finally, the geometry of the available foam block will fix the choice. The smallest block containing each blade has a 50 mm thickness, which means that the foam blocks would need to be glued together. Avoiding two many layers is a benefit in weight, resin used as glue being heavy. The process will also be easier, the tool drilling through resin layers. The final choice of foam is the M80, from which a detail is shown in figure 3.2.

Figure 3.2: Detail of the foam core.

Polyurethane expanding foam could have been used in a different process. This other processes will be developed later in this report. The foam would be even lighter, with slightly lower compressibility properties. It could be also used, as it is cheaper. But the process would need to be well set up, as it is hard to control its growth and its curing temperature.

3.1.3 Choice of the fibers

As shown in figure 3.1, the foam core would be machined to the exact designed shape. Then, the foam being compatible with Epoxy resin, fibers would be hand laminated on its surface. Carbon fibers would be laid up straight on the core, and finally covered by glass fibers. The glass fibers will therefore be in direct contact with the water during the stroke.

The choice of the carbon fibers has been quickly done. Mostly cosmetic, it had to cover completely the foam to hide it. The cover layer of glass fibers being transparent once cured, any misalignment of the carbon fibers would be visible on the final product. A fine enough pattern has been chosen for the above reasons, and to give a better uniformity of the impact resistance. As explained above, the body of the blade will need to resist small impacts during its transportation.

A 200 g/m² woven roving carbon cloth has been chosen 3.3, referenced as RC200T by the provider, SP-High Modulus. The twill pattern has been chosen for its availability and cost. It also contributes to the cosmetic. Other available fabrics were heavier: 303, 416 and 660 g/m². Easier to manipulate, they were all sold in a 1200mm width roll, which allow to cut the whole surface on one piece.

The shaft was reinforced with two layers of the same material, even though unidirectional fabrics could have been used instead. Easier to handle, two layers of carbon cloth is strong enough on the shaft connection, which is fairly long to provide a good fixity. This detail is studied later in this part.

Figure 3.3: Detail of the carbon fibers.

The choice of the glass fibers was influenced by several parameters. A fine fabric needed to be used to cover the carbon which is hard to sand. Sanding is a need to obtain smooth blades, which probably decreases the drag in the water by sticking the boundary layer to the blade. It would also reinforce the watertightness of the skins, even though the structural foam void connection is very low.

A 200 g/m² woven roving cloth has been used 3.4, referenced as EC200 by the provider, SP-High - Modulus. Some other weights of E-glass cloth were also available: 86, 165, 295, 301 and 400 g/m². Lighter fabric were avoided since they are hard to handle on shapes which are not flat. Heavier fabric were not needed, the paddle needing to be light, as mentioned earlier in this part.
3.2 Static pressure on the blade

Manipulated by strong athletes, the blades are subjected to very heavy loads. During the race, each stroke represents high stresses in the blade. At a regular pace, this would occur every seconds, on over 200 strokes to complete 1000 meters. The forces acting on the paddle had been estimated to avoid a catastrophic failure.

3.2.1 Forces acting in the stroke

The path of the blade in the water is complex, as shown by the motion capture. Then, following the streamlines of the water around the blade and computing the pressure and stresses on its surface could be an entire study. The present project was focusing on the highest stresses; producing the blade strong enough for these stresses would give a paddle which would not fail for any other stresses.

The blade is subjected to twist when it is up in the free air. In case of strong wind, the paddle would be twisted around its own axis, which is aligned to the shaft. Since it is hard for the athlete to keep the paddle in his hands in these conditions, this stress will not be high. A choice of a 0/90° woven fabric will make the paddle stiff in twist.

Some shear stresses are applied transversally, when the blade is moving sideways in the reference of the kayak. They only depend on the drag of the profile which has been designed, which can be neglected in comparison with the bending stresses in the paddle. All over the stroke, with its contact in the water, the blade is subjected to high bending moments.

The largest stresses are encountered during the entry of the blade in the water. They are the highest at the start of the race, when the boat does not have any speed. Then, the blade is pushed through a still water at high pace, on its largest wetted area. This force, perpendicular to the plane of the blade, causes a bending moment on the shaft, which is weaker because extremely thinner.

3.2.2 Maximum forces : bending

The velocities at each point of the blade can be calculated by the previous motion capture. Then, a discrete integration of all these values over the blade area makes possible to compute the bending moment at the junction with the shaft. The shaft itself is considered as very stiff and providing full support: it will give an over-estimation, and would avoid to catch and analyze the motion and strength of the athlete’s hands on the shaft.

This steps are repeated for each time step in a MatLab code, and the highest bending moment on the shaft is computed to be 220.8 N.m. A safety factor of 1.5 is used, which comes to a required bending moment of 331.2 N.m. The inner diameter of the shaft being 30mm, half of the carbon fibers will see 11.0 kN of compression, the other half 11.0 kN of tension.

The cover layer of E-glass is considered to be fully sanded and will not give any strength to the shaft. Carbon fibers having a higher strain in tension than in compression, the latter is the hardest requirement. For two layers of 200g/m² hand laid and vacuum reinforced cloth, the provider estimate the thickness of the skins to be around 0.45mm. Its compressive strength is supposed to be from 720 MPa. The achieved compression is calculated below:

\[ C_{ach} = \sigma_c \cdot \text{th} \cdot \frac{\pi \cdot d}{4} \]

This gives, with the previous values, a compressive failure of 15.3 kN. This gives a reasonable reserve factor on top of the safety factor used above. Two layers of cloth should provide sufficient support in bending for maximum loads. A slamming test in the water is recommended before use to validate this conclusion.

3.2.3 Structure with no failure

Standard blades are not only made of carbon, but have a steel rail on their tailing edge. This side of the paddle being exposed to rocks or any other kind of floor below the kayak, the steel edge has been on standard blades to prevent any failure due to a few shocks. Another option can be seen on other blades. To prevent the same
initiation of cracks, a local reinforcement of carbon has been added, which is resin rich.

The repetitive motion could also benefit from a fatigue failure study. Not only the fibers would then need to be studied, but also their bonds: from the structural foam to the fibers, and from the outer layer of the blade to the pre-made shaft. Generally, the athlete would change his paddle often enough not to climb in high fatigue repetitive motion numbers.

As in other industries using composite materials in their structures, a series of tests could be realized. Full scale tests varying the thickness of the reinforcement and its contact length in the shaft would give an accurate minimal weight to be used to be structurally viable. The manufactured paddle being as light as the standard one available in specialized shops, the above computation seems to be sufficient.

**Conclusion**

The design developed in the previous part showed a thickness which required a sandwich structure. The shell used in standard paddle could not be used, the materials could therefore not be simply copied for this project.

The sandwich will display a structural foam core, carbon fibers skins and an E-glass cover laminate. It will be hand laid-up with Epoxy resin, and reinforced in a vacuum. The details of the manufacture are explained in the next part of this report.

The foam was mainly chosen on three criteria: its light density allowing for buoyancy, its compressive strength to resist to possible chocks in water or during the transport, and its easiness to machine. M80 was the final choice.

The skins are made of light fabrics since the loads are relatively low on the blade. A cloth of carbon fibers will give some global stiffness to the blade, and give it its cosmetic. A thin layer of glass will make the blade easier to sand, being smooth being one of the design criteria.

The motion capture allowed to get the water’s velocity around the blade. A bending moment has then being computed, which stresses the shaft of the blade. A local reinforcement of carbon cloth has been computed to be necessary around the shaft.
CHAPTER 4

Building the sandwich prototype
How to build a sandwich prototype

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Introduction

A sandwich structure leads to a relatively complex process. To produce the paddle following the computed design with accuracy, and to lay up the layers as thought in the structural part, is not straightforward. A multiple steps process has been developed and improved. The core is CNC machined, the skins hand laid-up and reinforced with a vacuum. The final blade displays the designed geometry with a sufficient accuracy.

4.1 Machining a block of foam

Following the motion of the blade during a stroke, the design has been chosen to be 3-dimensional. This design and the structure it requires are quite surprising in a paddle’s manufacture. Previous blades were laid-up and compressed, often using pre-impregnated materials, called pre-preg in the composite materials industries.

4.1.1 A complex chosen design

The need to provide a 3-dimensional blade does not allow any of the actual process to make kayak paddles. Compressing whichever composite materials in a mold requires a constant thickness, for obvious manufacturers reasons. A structural core is needed in the construction of a blade where thickness varies from 5 to 30 mm.

Different ways of getting this complex shaped core were discussed. A wooden core, as used in many other sports products, was too heavy. It would have absorb some resin, and get even heavier. Then, a foam core was giving the best machinability - weight compromise.

Different products were discussed to obtain the most accurate structural core. A possibility could have been to machine two female molds, in medium-density fiberboard (MDF) to reduce the cost. An Endurathane expanding foam could then have constituted the structural core of the blade.

As shown in figure 4.1, the process is simple and can be repeated a certain number of times. Once machined, the two female molds are assembled. The expanding foam is poured in a very controlled amount. After curing, the core is released and the extra blocks of foam on the releasing holes are cut.

Figure 4.1: Process of a poured foam in female molds.
This process of getting the structural core is simple, cheap, and repeatable a few times for a same design. Nevertheless, it presents some drawbacks. The foam can expand to 20 times its volume and hit up to 100°C. The wood frame would need to be reinforced.

Another issue would be the quality of the mix. Endurathane foams are made of different components, two of them in most cases. Mixing always creates air bubbles, hard to release for thick materials, especially if the foam starts to cure straight after contact. It would result in unequal and fragile blades, if any large void is let in the structure.

On another hand, the wooden female molds are hard to design. They need to fit perfectly on each other; the foam provides a high contact pressure while curing, any small gap would dismantle the mold. Such molds would need to have complex shapes, which a contact plane between them which can not be a flat plane.

Figure 4.2 explains this impossibility. The left scheme shows a cross-section of the two molds that would need to be created. It would be hard to machine this cross-section properly. The right scheme shows the complex shape the molds should have, due to the twist of the blade.

Figure 4.2: Ways of machining the two female molds.

A last way had been thought, which would make the process twice as long in time. Creating the core in a medium-density fiberboard (MDF) might be possible. Then, creating two female molds would be easier, but more expensive for the materials we would need to use. Resin is to forget, such quantities are getting too hot while curing, even with the add of micro-balloons. A wax on which the temperature controls the viscosity would be preferable.

The final choice seems simple after these investigations. The structural core is made of foam, which is machined by a computer numerical control machine (CNC). Because of the low stiffness of this foam, the machining needs to be done in a few steps.

### 4.1.2 A multiple phases process

The foam chosen for the structural core is the M80 provided by SP - High Modulus. It is dense enough, but still bends significantly. Machining the whole block straight with a 6-axis CNC would not give any accurate result. The tool would push the foam and deform it from a few millimeters, even at short distances from the clamped part of the block.

The complex 3D design is transferred from solidThinking to GibbsCam, the software in charge of the machining, providing the path of the tool. The CNC will mill the foam block twice. The extra-dos of the blade will first be shaped, followed by its intra-dos. Figure 4.3 shows the whole process which has finally been accepted.

Figure 4.3: The manufacture process of the foam core.

It all starts with the shaping of the extra-dos of the blade. The CNC drills through the foam to create the exact shape of the blade on this side. The block is simply vacuumed on a table to clamp it. The extra-dos is chosen because the intra-dos is less of a 3-dimensional volume. Then, going deep into the foam block helps for the next step.

Some very fine plaster is poured in the cavity: Ultra-Cal 30, from Barnes Pattern Supplies Ltd. A cellophane paper and some wax should be applied on the shape to protect from the plaster. The side of the cavity should be free, so the casting would stick to the foam block. The more flat the casting is done, the easier it is to vacuum the composite then.

Once the plaster cured the block can be reversed, vacuum-clamped on the CNC table, and the machine can start drilling the intra-dos in the foam. The whole blade is then shaped. Cutting the edges allows to take it free from its casting and foam contour. Sanding the
whole job and especially its edges will make the design smooth, as it appears on the computer.

Choosing the material which would be used for the casting was hard. On some of the design, the CNC-machine wants to machine all the surface, not letting any foam on the outside of the blade’s contour. Then, the casting has to be very accurate to be able to vacuum the composite block for the second machining.

A first try was to machine the female part of the extra-dos and drill some holes in it to transfer the vacuum, as shown in figure 4.4. Then, applying the female mold on the foam would allow to vacuum the intra-dos. This process has to be perfectly realized, with a precision of less than a tenth of millimeter in the alignment of the two pieces.

![Figure 4.4: Vacuuming the foam through a casting.](image)

Another idea was to produce the female mold by directly applying a special wax or Endurathane foam on the shape, releasing it and finally drilling it. Casting fine plaster in the cavity was much easier; the plaster does not stick to the cellophane paper, but to the foam itself. Since both materials are clamped together, the need of drilling holes in the casting disappears.

4.1.3 Tips for a perfect foam core

The process has been through many tests, and improved a lot since the original idea. It is nowadays reduced to its minimum expenses, both in time and in cost. Some parts need an extra attention from the manufacturer, which are listed below, in the chronologically order they appear during the process of the structural foam.

The initial block of foam should be a perfect rectangular cuboid, with very flat surfaces. Once the block is vacuum-clamped on the table of the CNC, an operation gives to the machine its physical center. Touching the four sides with a specific finger will allow to compute this center. Then, if the block is not perfect, machining the other side would give an offset. The two faces would not be aligned.

The choice of the foam has already been discussed. This one was available with a 25 mm thickness only, and the design was fitting in a 50 mm box. Therefore, the two sheets needed to be glued together. It is capital to make sure that the glue is easily machinable. Resin 105 and its slow hardener 206 from West System Brand were used in this process.

To obtain a smoother surface, the CNC tool would need to do the same path different times with different offsets. Because the feeding head of the tool has a limited length, the foam can not be drilled perfectly straight away. An offset of 3 mm from the designed shape has been chosen for a first rough path, which takes about 1 hour. The second path is the finish, very precise, and takes around 4 hours.

Looking at figure 4.5, it is obvious that it is preferable to machine the extra-dos of the blade first. The left upper scheme shows the casting on the intra-dos, the right scheme shows the preferable casting. The more plaster will be poured into the cavity, the more chance it will have to stick to the walls of this cavity. Then, the vacuum on the table would have much more suction.

![Figure 4.5: Machining the extra-dos of the blade.](image)

The same way, it is better to be able to machine this face the way it is drown on the right scheme of the figure 4.5. The machining software might want to machine the whole face, which makes the casting harder, as shown on the left lower scheme on the figure. Casting twice is necessary, since the plaster loses water while curing, and therefore does not give a nice and flat final surface.

Once the blade is obtained, sanding the edges will be necessary. Sanding the rest of the blade is also recommended, to remove the licks of wax or plaster which may have been in direct contact with the blade. It will make the lay-up of the fibers easier, the resin being more compatible with the foam. Laying up the fibers on the 3-dimensional blade is a real challenge anyway.

4.2 The vacuum lay-up

The structure has been chosen to be simple: having the foam core, on which are superposed carbon fibers,
and then glass fibers. Each layer adding 0.6 mm of thickness, overlapping different layers would give an unaesthetic result. Carbon fibers are the main part of the structure, and give nice blades. Glass fibers add some structural strength, and are easier to sand after hand.

4.2.1 Manufacturing fibers

The way the blade has been designed requires a complex manufacture of the fibers. The blade does not have any symmetry, and does not have any straight line where starting letting the fabric on. The fibers were first cut with a rule of thumb, then adjusted on the foam core and cut again. Transferring the design to the software Abaqus allows to compute the shape and size that need to be cut.

Carbon and glass fibers need to be cut the same way, respecting this drawing. As illustrated in figure 4.6, all layers have to be assembled this way, from the middle to the top: foam core, carbon fibers, glass fibers, peel-ply, breather cloth, bagging plastic. The pipe on the right side of the figure is connected to the vacuum, which sucks the air, represented in red arrows. It is sealed to the vacuum bag with some tacky tape.

![Figure 4.6: Sandwich structure in the vacuum.](image)

For structural reasons, the layer of glass fibers should be replaced by a one-directional carbon fibers layer around the shaft. This will strengthen the shaft and avoid its failure in bending. Resin 105 and its Hardener 206 are chosen to impregnate all these layers. Mixing a quantity of resin at least three times the weight of the fibers is necessary.

Spreading the resin mix on the fibers and painting it quickly would avoid any fast cure and hit. Impregnating the resin with a roller helps the mix to go further in the fabric, and to wet all its thickness. The fabrics can then be applied on the structural foam core one by one, following the order given in figure 4.6. From the leading edge, rolling the fabric again helps to avoid keeping any air bubbles between the layers.

4.2.2 Vacuuming the job

Once the sandwich structure is laid as seen in figure 4.6, the resin has to start curing. Two or three hours after starting mixing the resin and its hardener, the vacuum bag can be sealed, and the vacuum pump switched on. The previous waiting time is an estimation of the pre-curing time of the resin, and the viscosity the mix would have at that moment.

If the vacuum is started too early, the resin mix will not be viscous enough, and the vacuum will remove too much resin from the sandwich. The fibers will then miss resin to reach their maximal strength and aesthetic properties. If it is started later, the mix will be very viscous, no resin will be sucked out. The blade will be heavier, the surface very rich in resin. The time estimation depends on the temperature: a higher temperature will make the mix cures faster.

Another way of processing the lay-up would have been to infuse the whole blade. With a same sandwich structure, feeding the bag with resin on one side and vacuuming the residual air on the other would bring the perfect amount of resin to the fabric. Though, this process requires to test different configurations, to be sure that the resin impregnates the whole blade. It is a serious issue with such a complex design.

4.2.3 Having a quality finish

The resin mix takes between 10 and 15 hours to cure with the 206 Hardener, according to the provider. Warming up the vacuum bag during the cure can help to have a shorter curing time. Unfolding the vacuuming bag and the layer of breather gives a paddle as shown in figure 4.7.

![Figure 4.7: Blade released from its vacuum bag.](image)

The leading edge is perfectly fitting, since the same fabric has been used for both faces. The trailing edge was obtained sticking the layers on each other. Rolling the layers was a way to avoid any air bubbles on this edge. Details are given in figure 4.8. The left photo shows the tip of the blade, the right one its shaft, both with the left-over fibers and resin.
The next step consists in trimming the trailing edge from the tip to the shaft with a band saw. An offset of 2 mm needs to be maintain, since the extra sandwich might vibrate. All the contour of the blade can then be sanded, as well as its surface. The aim is to get a blade with a very smooth surface, which is the exact model of the computed design.

A final step is then optional: coating the blade. That would make the surface even smoother, with a better penetration in the water. It would add some weight to the paddle extremities though, requiring an extra effort from the athlete to paddle efficiently. However, is a good way to have blades with the exact same weight, for a better weight balance of the paddle, and it allows to waterproof and protect the blade if some foam appears.

Conclusion

The chosen design, especially because it is 3-dimensional and sufficiently twisted, did not allow any of the classic processes. The structure of the sandwich had previously been chosen to fulfill many constraints and requirements, the manufacture was mainly focusing on two aspects:

- The manufacture of the structural foam core required full investigations and tests. Finally, a multiple phases process has been highlight. This process had to be reproducible for blades of different shapes and sizes. It has been thought to be the most accurate, relatively simple and cheap.
- The lay-up of the sandwich structure is another challenge in the way the 3-dimensional blade has a complex geometry. A hand lay-up had been preferred, with a controlled vacuuming and a quality finish. Finally, the blades available to test could come from a commercial well-developed process. Their shape fits the computerized design very accurately, their surface is very smooth and aesthetic.

The general process presented in this paper can still be improved in different ways. To produce a large series of blades, it might be more efficient and cheaper to manage to produce two female molds, and to get the structural foam core from them. This could be achieved with the use of expanding foam for instance, which would need to be previously tested.

Another consequent improvement would be about the lay-up of the fibers itself. A hand lay-up can be inaccurate in the quantity of resin absorbed. Vacuum bagging is a good way to extract the extra resin, but is still very temperature depending. Infusing the whole body would give a better and even more accurate and reproducible result.

Acknowledgments

Many people were involved in the preparation of this challenging process. The following person gave particularly precious advices, and followed the development of the process.

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CHAPTER 5

Trying it and getting feedbacks
How to try it and to get feedbacks

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Introduction

Testing and feedbacks are essential in a qualitative job. The feeling of the athlete using the improved paddle would be completed by recording the motion of the water around the blade. Since each blade would give different results, the feedbacks would finally be compiled to start over the whole process. They allow to rethink the design according to the new motion.

5.1 Survey and impressions

Most of the feedbacks are based on feelings. A survey with specific questions has been created to try getting precise informations on each part of the stroke. It has never been used, but could be the support to any start of a new design loop. The idea is to compare different effects of different blades on the athlete.

Another useful tool is the direct feedback from the athlete. Ian Ferguson as of a great help in this process since he had been thinking about for long of eventual evolution of the paddle. He also created the prototypes, to built blades which seems to a have a good feel.

5.2 Visualisation

As seen through this report, the motion capture is the key element of the design. It gives very useful data which can be easily interpreted and converted into a feature on the blade. The accuracy of the data is also extremely important, since small variations can lead to complete designs throughout this process.

5.2.1 Direct visualisation

A direct visualisation could be a first tool in the design improvement. Fixing GoPro cameras on the shaft of the paddle and recording a series of strokes could show the flow of the water around the blade. Particularly, it would show the possible cavitations around blade, or vortices in the water.

The presence of bubbles of the water would be of a great help to virtually draw the streamlines of the water. Such bubbles could also be artificially created, for instance if the kayak were to follow a motor boat. Or ink could be added to the water to partially color it. All these elements would allow a global understanding of the drag, but without any exploitable values.

5.2.2 Motion capture

As shown in the first part, the Vicon system can be used to record a very accurate position of the paddle. But it is used with fixed cameras in a solid room, which only enables the use of an ergometer. It is commonly known that the ergometer is a tool to help developing the muscles and the cardiac rhythm of the athlete, and does not reproduce exactly the paddling motion.
The Vicon system could be mounted on a tank, and record the motion of the athlete paddling in a fixed kayak. Such tanks are available, but the software will lose all the markers once submerged, and might not recover them. The data processing it involves is massive and probably hard to automate.

The same system could also be used on a lake to record the real motion. If the cameras are fixed, they would need to be many to cover a distance allowing at least a full stroke. At 20 km/h, this represent a length of 6 meters, and a width of 2 meters. If the cameras are mounted on boats, they should be steady enough to give accurate record data.

A similar technique has been used in an other study [2]. Different technologies have also been used in the past to record the motion of the body itself [7]. It has also been used and proved to work with accuracy on skiers skiing down a slope [12].

5.2.3 Other tools

Other devices could be useful to record data, which would require specific softwares or heavy post data processing to remove the noises. Some are referenced in [4]. The use of accelerometers has been proven to work in the past [8]. Different products exist with very different accuracies, and with an exponential cost.

Less common technologies could also be thought of. The use of pressure sensors [5], which would be wrapped around the blade, could allow the back compute the lift and the drag forces. A full study of the blade stiffness could allow the use of strain gauges. Glued all around the blade, they could give useful informations, which could be checked with a CFD model.

Finally, recording the muscle work on the athlete’s body would give some information. The energy lost by the athlete being proportional to the drag, such data would show which part of the stroke is energy consuming. The design could then focus on this particular aspect of the motion.

5.3 Further investigations

The previous technique are trying to loop the design process, to start over and affine the shape of the blade. Another design technique exists, which consist in trying different prototypes, and to compare them with the standard paddles. Different ways, other than the direct feeling from the athlete, can be thought of.

5.3.1 Time improvement

The simplest idea would be to competing on a certain length and to record the time. The acceleration phase would be avoided, only the steady state at maximum speed would be recorded. The different measurements would need to be taken in the exact same conditions, which is hard to achieve.

Any change in wind, surface of the lake roughness, physical condition of the athlete, would deteriorate the accuracy of the measurement. Also, even with significantly different blade, the difference in time to cover a given distance might be very small.

Another way of measuring the efficiency of a paddle compared to another could be to ask the athlete to try covering the maximum length with only a given number of strokes. The longer the distance the more efficient the paddle. This technique varies critically with the pace of the athlete.

5.3.2 Change in motion

Some of the visualisation tools described above could help track any variation in the blade’s motion during the stroke. Or the change in water streamlines around the blade. This would give a qualitative comparison between two paddles.

It would be needed to understand which parameters control which phase of the motion. Since the drag seems to be the easiest parameter to directly observe, through the size and velocity of bubbles and vortices, the comparison could help choosing a better design.

5.3.3 Change in muscle work

Some more measurements could be made directly on the body of the athlete. As explained above, measuring the global energy spent by the muscles would be representative of the drag. The tool could for instance measure the VO2 of the athlete in real time.

Measuring the effort of each muscle could also be a way to design personalised paddles. Every athlete is expected to have muscles stronger than other, or muscles which need less energy to produce the same strength over a period. If a design allows the athlete to spend less energy per stroke, the surface area of the blade could be increased. Then, using the same energy, the athlete would drive faster, the thrust being proportional to the submerged surface area.
Conclusion

This part is probably the most challenging. Several studies have already been trying to get feedbacks from athletes of different sports, facing the same problem. If a feeling can be obvious to the athlete, it is probably hard to explain with physical terms, and even harder to measure.

Different thoughts have been written in this part, which might help to introduce a second design loop. A survey and a discussion with the athlete testing the product is expected, to keep track of every feeling during the stroke.

Different techniques can be used, even simultaneously, to record the exact motion of the blade during the stroke. Derived of the motion capture presented in the first part of this report, they record the motion with different accuracies, and require more or less post data processing.

Another way of measuring the improvement of a paddle is to compare it to others, and the standard paddle used as a reference. Different measures can be easily performed, which give a qualitative result.

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I would like to thank Ian Ferguson, who gave me slow motion shots, which allowed to start the project by taking direct measurements. I would also like to thank Steven Ferguson, who was on the video shots, and who made the effort of accenting the motion to be clearly visible on the camera.
Conclusion

This project led towards the completion of a new kayak paddle which seems to be more efficient. It would therefore help an athlete completing a 1000 meters flat water kayaking race faster. This design has been obtained following different steps which are chronologically presented in this report, and summarized below. These steps could be repeated over and over in a design loop, to get a result tending to a perfect blade’s shape. Perfection would be the result of an optimization leading to the lowest time on a 1000 meters run for a given athlete.

The starting point of this optimization is the current kayak paddle, available on the market, and commonly called the Norwegian blade. Another reference blade has been given, as a prototype. The first step is an accurate analyze of the blade’s motion in the water, to understand the forces creating the thrust. Different measurements with different accuracies can be performed on video shots and on slow motions. They mostly lack accuracy due to the stability of a camera in situ, and to the fast motion they are trying to record: at a rate of 70 strokes/min, the blade travels in the water in less than half a second.

An accurate motion capture with a specific set-up and software allows to track and record such a motion with an excellent accuracy. Performed on an ergometer on two different athletes and at four different paces, it gives a better idea of this particular motion. The data is then available to create this motion in MatLab, and to back compute the streamlines of the water around the blade. Velocity, angle of attack and angle of application are recorded through the stroke, which leads to a specific design.

Avoiding heavy computations as CFD, a series of simple ideas and design criteria is extracted from the motion capture. The stroke is decomposed in three distinctive phases, with each their own preferences regarding the design. The entry in the water seems complex but would probably have some influence on the feeling of the athlete and its rapidity to catch the water. The pull-out phase can be assumed being a short steady motion creating lift. And finally, the exit of the water should minimize the curls and avoid the high splash of water currently observed.

The prototype and the first model are shaped to suppress this default, and the shape optimized to give the highest thrust during the pull-out phase. Driving the stroke, this phase is almost steady and has a similar Reynolds number to an aircraft wing. A database of NACA profiles can be used for this reason, which gives an accurate measure of the ratio lift over drag. At a certain angle of attack measured in the motion capture, a foil profile seems to be efficient and is tested.

A first prototype has been created using a CNC. The machine was drilling into a thick block of foam to create one face of the blade. This face was then coated with a plaster plug working as a support mould. It allowed the piece to stick in the vacuum bench of the CNC during the machining of the other face. The shape which had been worked in a CAD software was finally available with an excellent accuracy.

Adding the skins and reinforcing in a vacuum bag gives a blade very close from the theoretical shape designed earlier, with a smooth finish after sanding and coating with Epoxy resin. The reinforced shaft plugs were slotted into a tube, and the paddle was ready for testing. At this stage, recording the feedbacks from the athlete trying the blade is essential and has been discussed. It allows to refine the shape. By following the loop described here, one should be able to create a very efficient blade, with probably a similar shape.

The process is time consuming and an athlete would probably prefer to try different blades and to pick up the best one, instead of trying to give a physical meaning to his feelings. Certain phases of this project could be worked on to this end. From a given
motion capture, a design could be automated to give an optimized blade shape. The manufacturing process should also be accelerated.

Finally, some more ideas could be developed, which would bring this study to a whole new level. Using specific CFD and FEA models, the interaction liquid/solid could be evaluated. It would give a tool to answer simple questions. Does the blade’s surface need to be the smoothest? What about adding some relief on the extrados of the blade, as the one humpback whales have on their fins? Giving less stiffness to the blade would allow some deformability during the stroke, is there any way to optimize this to get even better shape in every phase of the stroke?

Some of these questions will probably be answered in other studies at the CACM. They will lead to a new development of the flat water kayak paddles, and might bring a significant improvement in Olympic performances!
Bibliography


