

Raoul Chappell Research methods 2021 Research Proposal

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Research Proposal for the Design Optimisation of White-Water Kayak Paddles

POSTGRADUATE RESEARCH METHODS (ACEA7003)

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Research Question

What is the optimum structural design of white water kayak paddles?

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1. Introduction

Whitewater kayaking is a sport where the participant propels their kayak down a fast-moving turbulent river using a paddle. The Kayak paddle works as a tool to transfer force from the paddler into the water, the resistance of the water to this force accelerates the kayak in the desired direction. The hydrodynamics of how the water flows around the paddle blade controls how the power is transferred from the athlete to the water and therefore into the acceleration of the kayak. There are a variety of factors that can significantly affect the hydrodynamic effects of the paddle stroke such as blade design, technique, distance from the kayak and the turbulence of the water.

There are three different types of white-water kayaking, recreational white-water kayaking where paddlers move down a white-water river with no competitive elements (Manby, 1999) as shown in Figure 2. Next is exploratory Kayaking where paddlers travel to rivers, waterfalls or rapids that have not been paddled before with the express purpose of completing a first descent (Dickinson, 1977; Heurteau, 2017).



Figure 1 First descent of the Malupa Rapid, Rhondu Gorge, Indus River, Pakistan (Lindsay, 2020)



Figure 2 Descent of Alexandra Falls, Hay River, Northwest Territories, Canada (Grady, 2018)

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Finally, there is competitive white-water kayaking where paddlers race against each other head to head or against the clock to be the fastest from start to finish. These races usually involve some key targets in some extreme white-water. Examples of these types of events can be seen below.



Figure 3 North Fork Championship 2019 (Leeds, 2019)



Figure 4 King of the Alps 2017 (Mai, 2017)

Unlike other forms of kayaking white-water kayaking is not an Olympic sport, many of the larger competitions are also not supported by the International Canoe Federation (ICF). However, there is an emerging discipline called extreme slalom that combines aspects of both white-water kayaking and slalom kayaking. In extreme slalom athletes race head to head on a modified course where there is much higher likelihood of hard contact between the athletes and their equipment (International Canoe Federation, 2021).

As the sport progresses by finding new locations to paddle, bigger, harder rivers with higher consequence of failure or increasing prominence at an international level. A commonality between both areas of the sport is paddles need a high level of stiffness and strength to be able to withstand the forces acting on them, while also providing the maximum power transfer possible between the athlete and the water allowing faster acceleration of the kayak. The goal of this project is to optimise the structural design for composite materials in white-water kayak paddle manufacture to increase the strength and stiffness of the product.

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2. Research Aim and Objectives

To complete this project specific research aims must be used to ensure that the project remains on track. Within each of these aims several objectives will be used as more specific tasks that must be completed to achieve the research aim.

2.1. Research Aim

To use computational analysis and simulations to determine the optimum lamina stacking sequence to limit the stress concentrations in white water kayak paddles whilst maintaining a lightweight product.

2.2. Research Objectives

- To use a combination of computational analysis and simulations along with secondary research data determine the lift and drag forces acting on the kayak paddle blade whilst in use.
- To analyse the effects of key design features from different kayak paddles and how they affect the forces acting on them.
- To determine how these key design features affect the performance of the kayak paddle.
- To use the forces calculated from the computational analysis determine where stress concentrations are located within the product and what the largest magnitude of stress is during use.
- To use laminate failure theories to minimise the effects of stress concentration zones and to strengthen the paddle whilst also limiting any additional unnecessary weight.

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3. Literature Review

This section will review a wide variety of literature on the topic areas detailed in the research objectives these include forces acting on kayak paddles, the calculation of lift and drag forces, previous designs and materials, calculation of magnitude and location of stress concentrations and theoretical optimisation methods.

3.1. Forces Acting on Kayak Paddles

Kayak paddle blades are where the power transfer between the paddle and the water happens, therefore has several forces acting on it, additionally, the forces applied to the paddle shaft should not be neglected as they also influence the stress concentrations seen during use. This is displayed below in figure 5.



Figure 5 Whitewater kayaker taking a forwards paddle stroke (Barwick, 2019)

In Figure 5 the athlete pushes forwards with their top hand while simultaneously pulling back with their bottom hand. When this is combined with the flow of the river and the resistance against the paddle blade this creates a macroscopic three point bend test.

A small number of papers have studied these forces (Stothart, Reardon and Thoden, 1986) first developed a system to measure the force applied to a kayak paddle by implementing strain gauges to measure the bend in the shaft which could be used to calculate the force applied to the paddle. In a comparative biomechanical study (Fleming *et al.*, 2012) used strain gauges attached to both a Kayak ergo and a paddle used during on water testing and calculated an average peak force of 223N for the Ergo and 238 for the on water testing. In contrast, (Springs *et al.*, 2006) conducted a similar study using force transducers attached to a kayak ergo and measured an average peak force of 270.4N, considerably higher than the average calculated in (Fleming *et al.*, 2012) therefore further research into or testing of these values is required.

Other forces that should be considered in this project include impact on rocks or other objects in the river as well as being used as a reaching implement on rescue scenarios.

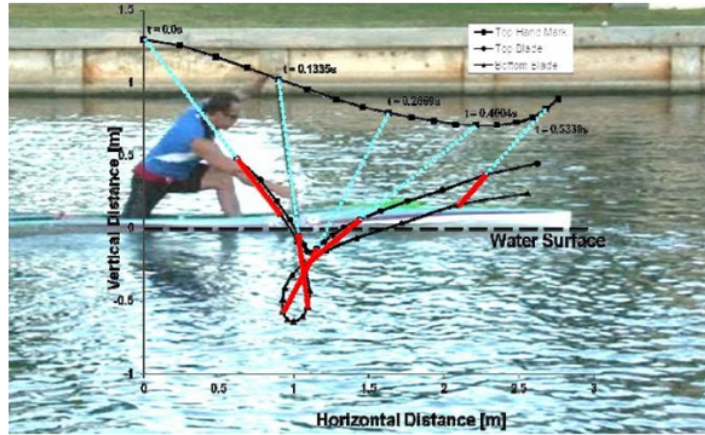
3.2. The Calculation of Lift and Drag Forces.

Lift and drag are the two primary hydrodynamic forces that act on the paddle as it is pulled through the water (Morgoch, Galipeau and Tullis, 2016). In this study the lift will be considered as the vertical component of the water's resistance to movement. This is caused by the paddle blade entering the water at

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an angle a portion of the force created by the water flowing past the kayak will therefore be acting to push the paddle vertically up out of the water. In this study drag will be considered as the horizontal component of the water flowing past the kayak and resistance to change in direction.

To enable this study to be achievable within the timeframe and scope of this project a decision has been made to run the simulations as several static studies at key stages in the paddle stroke. Because the paddle blade changes angle as the athlete pulls the paddle blade through the water shown in figure 6 several simulations will need to be completed and analysed to obtain the best representation of what happens to the fluid flow and the forces at each stage. provided that the results correlate this will enable an estimation of



the resultant force on the paddle blade throughout the paddle stroke.

Figure 6 Video Still of Canoe Sprint Athlete with Superimposed Blade Path as Traced by Tracking Handle Points(Dana Morgoch, 2016)

To calculate the lift and drag forces acting on the kayak paddle the coefficient of lift and drag must be calculated. The coefficients of lift and drag are dimensionless values that are used to consolidate many of the complex dependencies such as shape, flow characteristics and incline. These values are collected experimentally or from computational simulations. The equations for lift and drag are shown below.

$$L = \frac{C_L \times \rho \times A \times v^2}{2} \quad \text{Equation 1}$$

$$D = \frac{C_D \times \rho \times A \times v^2}{2} \quad \text{Equation 2}$$

(D. Morgoch, 2016)

The lift and drag values will be used to calculate the magnitude and direction of the resultant force acting on the paddle. This will be used to calculate the stress in key areas to enable a better optimisation of the composite stacking sequence.

In their paper (Sumner *et al.*, 2003) conclude that of the three designs tested (standard, Norwegian and turbo) the change in design had little effect on the coefficient of drag. There has been very little research in this area to either substantiate or refute these conclusions. If this report can confirm these conclusions then the only noticeable change to the drag and therefore the propulsion of the kayak would be the surface area

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of the blade. This would mean that the design of the blade only affects the way in which the paddle blade moves through the water.

3.3. Previous Design and Materials

Since the first Kayak paddles used by the Inuit there have been a wide variety of designs of kayak paddles. Kayak paddles have diversified in both design and materials as new disciplines of the sport are developed



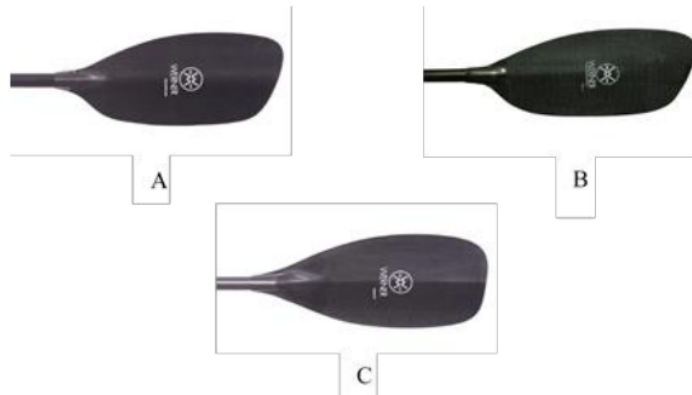
for example many sea kayakers prefer to use a traditional Greenland paddle shown below in figure 7 which is very different to modern white water paddles shown below in Figure 8.

Figure 8 Wooden Greenland Paddle(east pole paddles, 2021)



Figure 7 Werner straight shaft white water kayak paddle (Werner Paddles, 2021d)

The whitewater kayak paddle consists of a shaft which can either be straight or cranked (asymmetric bend to increase ergonomics) and two paddle blades one at each end as shown above. The Paddle blades on white water kayak paddles tend to be asymmetrical and slightly concave (on the power face) to increase the amount of water that can be moved by the paddle stroke thereby increasing the resistance against the paddle blade increasing the propulsion of the kayak (Olympic Outdoor Center, 2021).



More recently paddle designs have been diversifying further. Within white water kayak paddles there are different designs for recreational white water and competitive white water racing as shown below. The below Figure displays some of these variations from a single popular kayak paddle manufacturer.

Figure 9 Different designs of white water kayak paddle blades (A) Werner Powerhouse (B) Werner Stikine (C) Werner Odachi (Werner Paddles, 2021b, 2021c, 2021a)

The Werner powerhouse shown in figure 9 is a standard white water kayak paddle designed for use on a wide variety of levels of white water. The blade has a dihedral shape that is reported to provide a smoother

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more stable paddle stroke by reducing the lateral movement of the blade also known as flutter (Werner Paddles, 2021b).

The Werner Stikine is much like the powerhouse in that it has been designed for use on a wide variety of white water, however, with its longer narrower shape the paddle is reportedly better suited to longer trips where the paddler's physical fatigue may become a factor. the blade is also flatter than the Powerhouse or the Odachi meaning that there would be increased flutter (Werner Paddles, 2021c).

The Werner Odachi was designed for competitive white water kayaking with a larger more symmetrical blade for increased propulsion and an increased shaft to blade offset allowing for a smoother entry into the water also it keeps the blade more vertical throughout the stroke. Finally, a more aggressive dihedral shape is added to counteract the larger size of the paddle blade reducing flutter and physical fatigue on longer races (Werner Paddles, 2021a).

The final feature that should be considered is how the paddle blade and paddle shaft are joined together some paddle manufacturers produce monocoque paddle halves meaning that the paddle blade and the corresponding half of the shaft are manufactured in one piece this reduces the potential for stress concentrations however does increase the cost of replacement if damage did occur. Other manufacturers however use an adhesive and contact fit to join the sections of a paddle (GPower Paddles, 2021; Werner Paddles, 2021b). This feature will be investigated to determine whether the reduction in stress would be worth the risk of the additional expense if the paddle became damaged.

This project will analyse the effects that these design features have on the lift and drag forces applied to the kayak paddle and what affect this would have on the performance of the paddle blade.

3.4. Calculation of Magnitude and Location of Stress Concentration Zones

The force data collected from the fluid dynamics study will be used to create a finite element analysis study to calculate the stress concentrations on the paddle. Because it is unlikely that the kayak paddle would become damaged purely from force applied pulling it through the water a further study will also be completed to analyse the stress concentrations when the paddle blade comes into contact with a solid immovable underwater object (rock, tree etc). To streamline this study, the simulation will be set up at the blade position where it is already under maximum stress from the fluid flow and the constraints will also be set in a "worst case scenario" position where the immovable object stops the paddle blade at the furthest point from the force application, the lower hand on the paddle shaft.

The maximum deflection of the paddle blade will also be calculated during the simulations because in terms of performance an ultimately stiff paddle would provide a better power transfer as none of the energy would be absorbed by the paddle, however, this limits the ability of the paddle to distribute applied loads making it more likely to become damaged under the same loading conditions. Therefore, a small amount of flex is necessary to prevent the paddle from becoming damaged too easily without causing a large decrease in power transfer (Staab, 2015).

3.4.1. Validation Methods

The finite element analysis simulations will be validated using physical testing provided local covid-19 restrictions allow. The methodology for the physical testing will be determined once the project has begun.

To calculate an estimated value for the stress magnitude a number of assumptions must be made including geometry simplifications and linear analysis. This will allow the calculation of an order of magnitude estimate of the stress that will be calculated during the FEA simulation.

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3.5. Theoretical Optimisation Methods

To optimise the structural design and the lamina stacking sequence a combination of classical laminate theory and FEA will be used. When using classical laminate theory the failure criteria must be considered. (Soden, Hinton and Kaddour, 1998) produced a journal article on the comparison of predictive capabilities of current failure theories for composite laminates and found that even at the most simplistic level (unidirectional fibre reinforced lamina) there is a large difference between the failure envelopes from each method varying up to 570%. For this reason, further research should be carried out into the potential failure theories before the decision is made regarding which to use in the theoretical optimisation of the laminate for the kayak paddle.

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4. Research Methodology

4.1. Saunders Research Onion

Saunders research onion developed by (Saunders, Lewis and Thornhill, 2007) is a structural guide to the development of a research methodology. Saunders research onion structures the decisions on how the research methodology will be shaped, there are six layers to a research onion philosophy, approach to theory development, methodological choice, strategies, time horizon and techniques and procedures starting at the outermost layer with research philosophy, the researcher progresses inwards whilst shaping their research methodology. The selections for each layer of the research onion are detailed below (Saunders, Lewis and Thornhill, 2019; Crossley, 2021)

4.1.1. Philosophy

This research project relies both on mechanical and mathematical data together with interpretation and continuous questioning of this knowledge, therefore a pragmatic approach to the research is most applicable.

4.1.2. Approach to Theory Development

There are two main approaches to theory development the first being inductive where there is little knowledge about the research area, therefore, the research would need to be conducted to enable the researcher to gain information to form their theories. The second is deductive where the research area has been studied and established prior to the researcher forming their own theories. As there is little research in the area studied in the proposed project the researcher aims to take an inductive approach to this research project.

4.1.3. Methodological Choice

This research project will use a combination of qualitative and quantitative research, the data from the CFD and FEA studies will be analysed both mathematically and interpretatively to determine where the research should progress next, therefore a mixed methods approach will be used.

4.1.4. Strategies

This research project will use a combination of experimental research and grounded theory strategies, there will be experimentation conducted to determine the effects of key design features of white-water kayak paddles on their performance as well as testing potential lamina stacking sequences. However, as there is little research available on the proposed study the data collected at each stage will be used to inform decisions as the project progresses. this will enable the formation of a theory as the project progresses.

4.1.5. Time Horizon

The time horizon refers to when the data is going to be collected for the CFD section of this project. Results will be collected at multiple points during the paddle stroke, therefore, this would be considered cross sectional as the analysis is both of the data at that point and how it changes through out the stroke, however, the FEA section of this report would be considered longitudinal as the data will only be collected at that point in time.

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4.1.6. Techniques and Procedures

Initial Research

The initial research conducted will comprise of secondary research sources from a variety of research mediums, the main focus of research will be from journal articles and research papers.

Modelling

SolidWorks 3D CAD software will be used to model the kayak paddles using surface tools and

CFD

There are several techniques and procedures that will be used when conducting the CFD simulations and analysis these are detailed below.

Base Case

The base case is the first simulation run during a study using estimated domain dimensions and a coarse mesh size this allows the simulation to be calculated quickly but not very accurately. This is conducted to better inform the analyst on where to proceed during the next two stages.

Domain independent study

The Domain Independent Study is used to ensure that the domain in which the study is conducted is large enough that its size will not affect the outcome of the analysis but not so large that it will take too long for the simulation to calculate. In a correctly dimensioned domain the fluid should have returned to laminar flow before the outlet and the inlet should be placed ahead of any turbulence seen in front of the studied object the same with the walls they should be far enough away from the body that the fluid flow affected by the studied object is not also affected by the domain walls preventing errors in the results collected.

Mesh independent study

The mesh independent study is similar to the domain independent study where an aspect of the mesh is changed in between each simulation to determine its effects. The mesh independent study is used to determine the mesh size that should be used during the analysis. the reason for this is a finer mesh is more accurate than a coarse mesh, however, it takes much longer to solve, therefore, the goal of the mesh independent study is to determine a mesh size where the coefficient of lift and drag stabilise that does not take too long to simulate. Once the mesh independent study has been completed the domain independent study will be revisited if necessary.

Test Simulation

During the test simulations the domain and mesh settings will remain constant, however, the pitch angle of the blade in relation to the flow will be changed to analyse the forces acting on the blade at different key points within the paddle stroke. This will be completed for each of the paddle blade designs before they are analysed to determine the differences caused by key features.

Post Processing and Analysis

The post processing of the simulations will involve the collection and analysis of the results from the test simulations; these will include the velocity and pressure diagrams along with streamlines to further analyse the affects that the paddle blade is having on the fluid flow and what that subsequently means in terms of performance. This will be used to optimise the design of the paddle.

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FEA

The FEA will use the force data collected during the CFD analysis to determine the location and magnitude of stress concentrations, these can then be used to calculate the number of plies and the best orientations so that an optimum stacking sequence can be created for the paddle.

4.2. Research Timeline

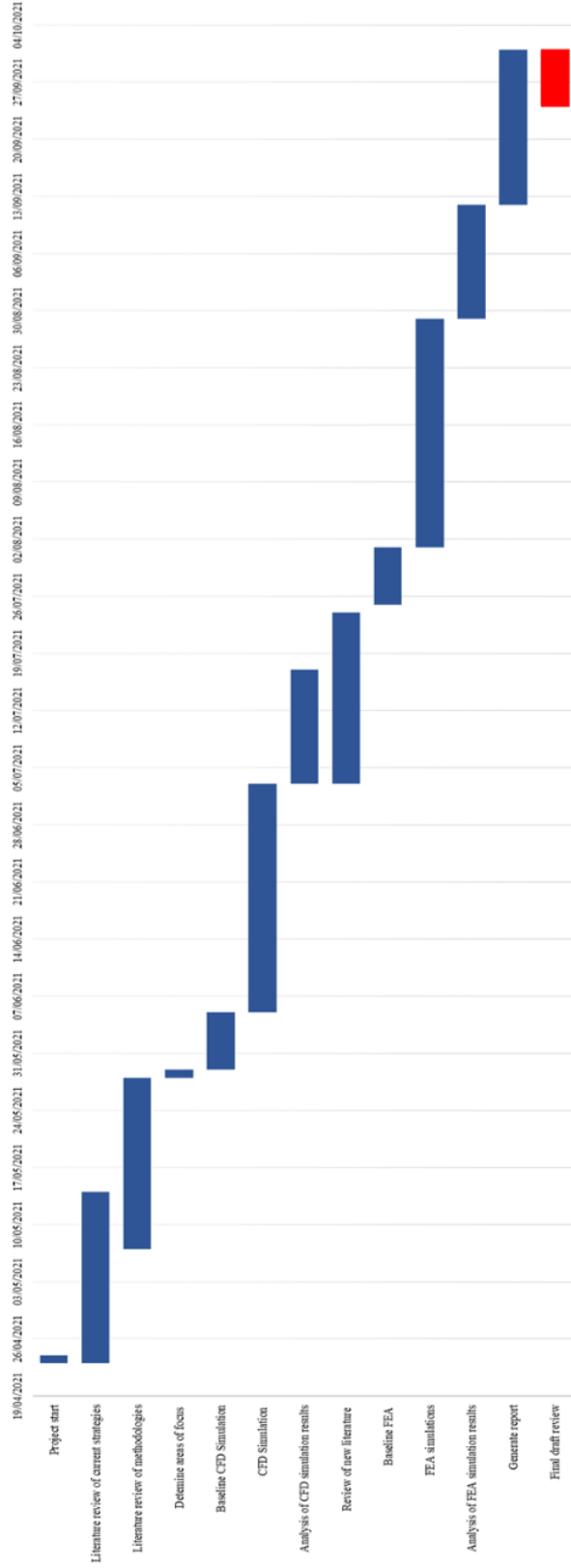


Figure 10 Project Gantt Chart

It should be noted that the Gantt chart shown above is a working document subject to reasonable change

5. Results and Analysis

5.1. CFD

A wide variety of results will be collected from the CFD analysis mainly in the form of screenshots that can be analysed whilst the subsequent simulation is solving. The results collected will include;

- pressure location and magnitude
- velocity location and magnitude
- length of wake region
- pressure in wake region behind paddle blade
- vortex size, shape angle and position
- images of pressure gradient velocity gradient and streamlines
- the pressure location and magnitude will be used to calculate the forces acting on the kayak paddle blade during use
- the velocity and streamlines along with the images of the pressure and velocity gradient's will be used to analyse the flow patterns around the kayak paddle blade to aid in determining the effects of key design characteristics.

Where appropriate these results will be analysed quantitatively, however, some of the results will need to be analysed qualitatively by comparison between simulations and with secondary research.

5.2. FEA

The initial FEA study will collect results on the location and magnitude of stress concentrations that will be analysed quantitatively while using classical laminate theory to determine potential lamina stacking sequences. Once developed the lamina stacking sequences will be modelled on the kayak paddle and the simulations completed again to determine the effect that each has on the deformation of the paddle in both loadcases.

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