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Designing a paddle blade
Fluid flow assessment
Structural and Fluid Analysis

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1 Introduction

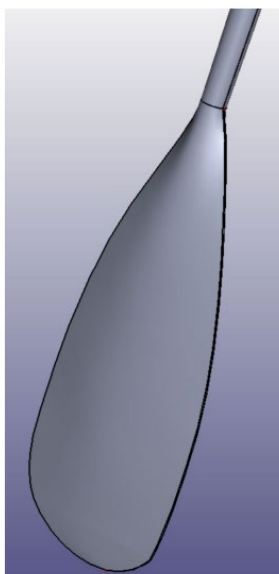
Kayak paddles and their blades are all relatively similar in appearance, but small changes in their geometry and material selection can have a much greater effect on the fluid dynamics around them, and as such their performance. Recent progressions in numerical modelling techniques have enabled great improvements in their design and allowed a much wider understanding of the flow conditions they face in the wide range of uses they may be subjected to.

This report will discuss various aspects of paddle blade design, as well as investigating some of the fluid flow characteristics they may face. It will cover paddles in general, while also considering one concept for a paddle blade, shown below in Figure 1.

Firstly, the blade will be evaluated with consideration to the Reynolds Number of the flow around it, discussing the importance and influence of this on the flow. It will then discuss the boundary flow over the surface of the blade, with consideration to how this may differ between different usage scenarios.

As with any engineering problem, material selection is important, so the selection of glass-fibre reinforced plastics will be assessed with regard to its intended use, and the implications of this on its performance.

Finally, an overview of various CFD modelling techniques will be given, before an experiment methodology is presented with the aim of validating the modelling technique that will be implemented on the given blade.



2 Reynolds Number

The Reynolds number is the flow parameter that is used to determine flow regime: laminar, transition or turbulent, and to what degree. It is dimensionless, so its use relies solely on the knowledge of what values are considered laminar, and what are turbulent; this transition point found in historical experiments for any given scenario.

Derived from the ratio of inertial forces to viscous forces, it is given below:

$$R_e = \frac{u \cdot l \cdot \rho}{\mu} = \frac{u \cdot l}{\nu}$$

where:

u : velocity (m/s)

l : significant length (m)

ρ : density (kg/m³)

μ : dynamic viscosity (kg/m.s)

ν : kinematic viscosity (m²/s)

In low Reynolds Number cases, the viscous forces are great enough to overcome the inertial forces, so the laminations within the fluid are maintained (Conner, 2019). At greater flow rates, the velocities of fluid particles are high enough that any disturbances can disrupt their path, so that their inertia can overcome the viscous forces, causing the erratic paths seen in turbulent flow.

The most efficient transfer of power from the paddle to the water would involve as little turbulence as possible, as any areas of water moving forwards show energy lost. Where the paddle will be moving slowly in relation to the water, this low velocity can allow a greater significant length while maintaining the same value of R_e . Therefore, where the paddle will be moving faster in relation to the water, a lower significant length would increase power transfer.

As with many blades and aerofoils, a useful place to measure the Reynolds Number is across the power face, where the chord length is at its maximum; the same technique Sumner (2003) used in their study of kayak paddles. Similarly, a 1 m/s relative velocity is applicable for a general estimate of R_e in normal use, and a dynamic viscosity of 1.0016×10^{-3} kg/ms at a water temperature of 20°C. For this paddle, the maximum chord length is 192mm, taken from the CAD file. This produces a Reynolds Number of 1.92×10^5 as below:

$$R_e = \frac{u \cdot l \cdot \rho}{\mu}$$

$$R_e = \frac{1 \cdot 192 \times 10^{-3} \cdot 1000}{1.0016 \times 10^{-3}}$$

$$R_e = 1.92 \times 10^5$$

3 Boundary Flow

The boundary flow is the region in which the viscous effects caused by interaction between the fluid and an objects surface are significant. A reduction in velocity is always seen in this region, and there are vortices present. For fluid in direct contact with the surface on the blade, there is no relative velocity – an assumption known as the ‘no slip’ condition (Liburdy, 2021). Moving away from the blades surface along its normal, the relative velocity increases until it reaches a point where it is equal to the relative velocity of the surrounding water, be it the static water of a pond, or the flow rate of a river. This region in which the velocity increases away from the surface is the Boundary Layer.

When considering the steady state of a flow parallel to a surface, the boundary layer can be seen to get wider further from the first point of contact with the surface, as seen in Figure 2. This is due to the T-S waves which grow in amplitude, disrupting the flow path of the fluid, destabilising until the flow becomes rotational (Burke, 2009).

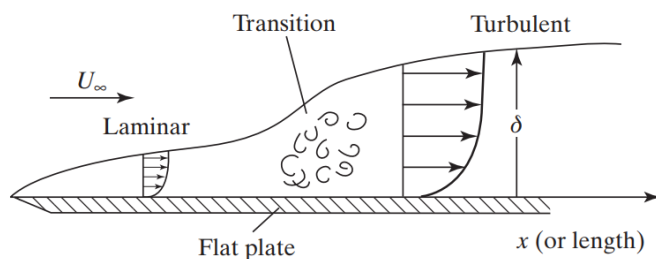


Figure 2 - Schematic of Boundary Layer (Katz, 2010)

In the case of this paddle, the paddler holds the blade so that its face is near perpendicular to the direction of travel, so the relative flow contacts the blade surface from a direction somewhere near to its normal. As the angle of attack of the blade orients the flow towards the trailing edge, and the blade is shaped to shed vortices towards the rear, it can be assumed that the proportion of flow that contacts the blade and flows towards the front edge is negligible – as such the flow can be approximated to flowing parallel to the blade as if it were a flat plate, as above.

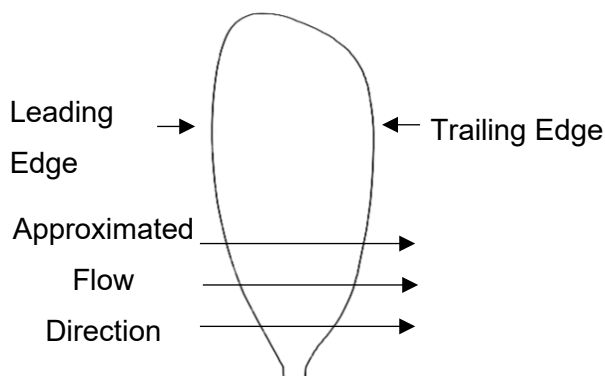


Figure 3 - Diagram for clarification

At the leading edge, the boundary layer will be at its thinnest, as the T-S waves have not yet formed. However, the flow outside of the Boundary layer will not be laminar as displayed in Figure 2, because the Reynolds Number calculations from the previous section show that the flow is already turbulent. The velocity gradient typical shown in will be present.

Moving away from the leading edge, the Boundary Layer will widen, so the velocity gradient will occur over a greater distance along the normal, and vortices which form and grow due to flow separation within the boundary layer.

At the trailing edge, the boundary layer will be its widest. The vortices present will hold their maximum energy at this point, as they will start to widen but dissipate as they shed from the blade's surface. The fully turbulent flow inside the Boundary Layer will mix with the turbulent region outside of it.

When used in still water or a calm river, the flow outside of the Boundary Layer may be laminar, so the Reynolds Number at any point in the system will be lower. As the Boundary Layer grows along the blades chord length, the lower Re means a greater chord length is possible before the Boundary Layer reaches the same width. This allows the use of a wider blade in less turbulent water, which allows greater power transfer.

In more turbulent water, a narrower blade, i.e. one of shorter chord length, is necessary to reduce Boundary Layer width and increase power transfer efficiency. This is also better in terms of reducing undesirable sideways forces on the blade and allowing a faster stroke speed.

Conversely, in extreme white water, paddling efficiency is overruled by the principle of conservation of momentum. A kayaker may want to propel themselves forwards with one stroke, so they must displace as much water backwards as they can – for this a much larger paddle may be desirable, despite the greatly reduced power transfer efficiency.

4 Material Implications

For the benefit of the performance of a paddle blade, the stiffness of the blade should be a maximum, to ensure little energy is lost during the stroke. There are two elements to this: the stiffness due to the structure of the blade, and that due to the Young's Modulus of the materials chosen.

For much of their history, oars and paddles have been made from wood, as it was the best and often the only material option. It is only since the latter half of the 21st century that plastics have allowed further advancements in paddle blade design. As shown in Figures 4 and 5, the thermoplastics used in paddle blades, such as HDPE and ABS, do not have as high stiffness or strength values as wood, but they are much cheaper to mass produce. More traditional wooden paddles may be stiffer when subjected to stress throughout the stroke, but they demand much thicker sections, so are heavier – a key variable when considering paddles are used for hours at a time (BestMarineOutdoors.com, 2021).

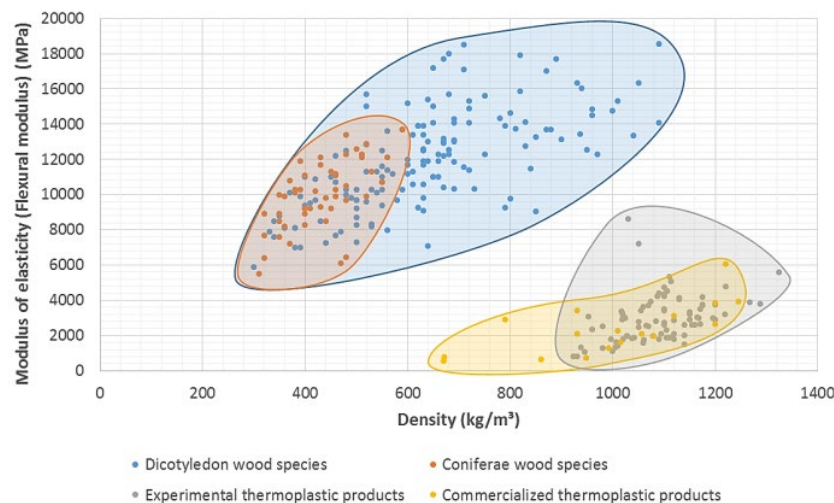


Figure 4 - Modulus of elasticity for woods and thermoplastics (B. Z. Diaz, 2016)

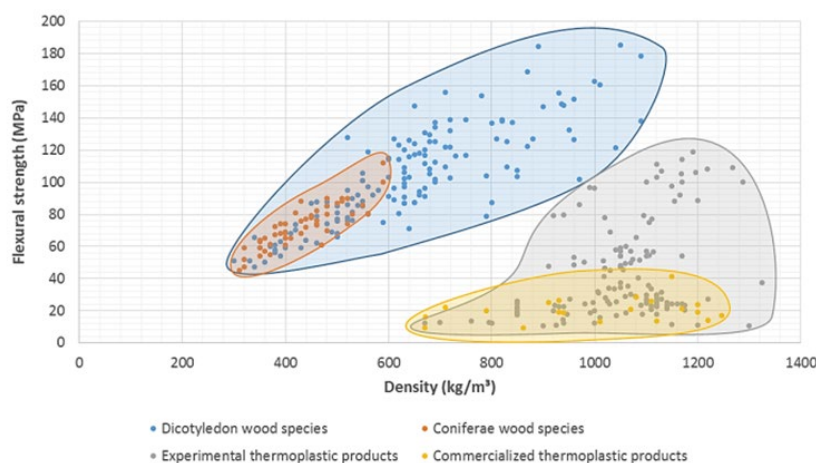


Figure 5 - Flexural strengths of woods and thermoplastics (B. Z. Diaz, 2016)

Composite materials have been instrumental in allowing a new wave of advancements across engineering, mostly for their ability to achieve necessary stiffness and strength values with incredibly low densities. The lower cost composites like the glass-fibre reinforced plastic that will be used for this paddle are the most popular in high-end paddles, as they are significantly cheaper than carbon-fibre alternatives, but much lighter, stiffer and stronger than thermoplastics or wood (BestMarineOutdoors.com, 2021). They are also hard, so damage such as dents or scratches that will affect the part's integrity and fluid flow characteristics are less likely.

Carbon-fibre reinforced plastics are considerably more expensive, as the fibres themselves are more costly to manufacture. They generally hold higher strength values than glass-fibres, as can be seen in Table 1, but this depends heavily on the specific matrix-reinforcement combination (Ngo, 2020). As manufacturing methods continue to become faster and more efficient in the future, the costs of these materials will come down, enabling more users to access the current high-end technology.

The material choice will also dictate the structural element of the design. Composite technologies allow much greater design flexibility and shape complexity (Ngo, 2020). A construction of glass-fibre reinforced plastic allows the internal structure to be hollow, with a solid skin supported by internal ribbing. If the blade were to be made from lower cost plastics such as polyethylene or ABS, then they would not be able to be made in the same manner. They would likely be made through injection moulding, so it would not be feasible to make them hollow with a ribbing structure inside.

Table 1 - Properties of several fibre-reinforced polymer composites (Ngo, 2020)

Composite	Density (g/cm ³)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
ABS + 30% glass fibre	—	2.0	60.0	9.0
Acetal copolymer + 30% glass fibre	—	3.0	110.0	9.5
Epoxy + 40–60% carbon fibre	1.15–2.25	0.4–11.0	4.6–3220.0	2.6–520.0
Epoxy + 45% flax yarn-aligned	—	—	133.0	28.0
Epoxy + 40% glass fibre	—	—	—	—
Epoxy + 52% jute fibre	—	—	216.0	31.0
Epoxy + 52% kevlar fibre	—	—	434.0	28.2
PEEK + 62% carbon fibre	1.60	—	750.0	50.0
PEEK + kevlar fibre	1.31–1.50	1.0–6.0	75.0–193.0	4.0–20.7
Nylon 66 + 25–30% carbon fibre	1.20–1.57	0.90–4.0	193.0–261.0	16.0–33.1
Nylon 6 + 40% glass fibre	1.45	2.0–3.0	235.0	12.9
Nylon + kevlar fibre	1.16	4.0	110.0	9.0
PLA + 30% abaca fibre	—	—	74.0	8.0
PLA + 20% bamboo fibre	—	—	90.0	1.8
PLA + 30% flax fibre	—	—	53.0–100.0	8.0
PF + E glass fibre	1.5–1.65	—	85.0–330.0	5.0–17.0
Polycarbonate + 5–40% carbon fibre	1.15–1.43	0.9–118.0	46.0–186.0	2.1–25.5
Polycarbonate + 30–40% glass fibre	1.44–1.52	4.0	107.0–159.0	10.0–11.6
Polycarbonate-ABS + 30% glass fibre	1.29	—	82.7	—
Polyimide + 20–30% carbon fibre	1.38–1.68	0.8–5.5	36.5–241.0	4.5–29.0
Polyimide + glass fibre	—	2.0	150.0	12.0
PP + 30% carbon fibre	1.07	1.0	117.0	16.2
PP + 30% cotton fibre	—	—	58.5	4.1
PP + 20% glass-chopped strand mat	—	—	77.0	5.4
PP + 20% glass fibre	1.03	3.0–4.0	100.0	4.3
PP + 40% glass fibre	1.22	2.0	127.0	7.6
PP-MAGPP + 40% hemp fibre	—	—	52.0	4.0
UPE + 35% jute fibre	—	—	50.0	8.0
UPE + 47% glass fibre	—	—	201.0	13.0
Vinylester + carbon fibre	1.50–1.65	1.4	900.0–1200.0	136.0
Vinylester + 24% flax fibre	—	—	248.0	24.0
Vinylester + 59% glass fibre	—	—	483.0	33.0
Vinylester + kevlar fibre	1.35	—	500.0	40.0

5 Modelling Techniques

Historically, flow around this blade would have been assessed analytically, with complex mathematics derived from the Navier-Stokes equations. This approach can eventually produce exact values for almost any parameter that you calculate, but it doesn't offer the wider understanding and visualisation that modern CFD programmes excels at. Although the hand calculations present the risk of human error during the calculations, they present less risk of misunderstanding as they are less accessible than numerical programmes.

Computational Fluid Dynamics encompasses any programme which uses numerical techniques to calculate flow parameters. The calculations can often a significant time to solve, where simple hand calculations can sometimes take only a few minutes to find a useful value. CFD programmes, as with all modelling techniques, are only ever approximations, though as fluid flow is subject to so many variables that it would be impossible to model perfectly. They are also prone to human error at the pro-programming stage, which may produce a visually impressive but completely inaccurate and potentially dangerous result.

The numerical solving done by CFD programmes use different solver methods, each applicable to different flow scenarios. The main solvers used in CFD are the Finite Difference Method, Finite Element Method, Finite Volume Method and Spectral Method, although there are many others, as well as variations of these four (N. Ashgriz, 2004)

The Finite Difference Method uses Taylor Series expansions and therefore relies on a regular grid, so cannot handle a mesh that differs in boundary geometry (G. Tschirschnitz, 2020) This regularity does translate to faster solution times though, and it can be helpful when comparing different data sets from the same system.

In Finite Element Method solvers, the system is divided into connected elements, with complex differential equations done for each. Although most widely used in stress analysis scenarios, it can be applied to fluid dynamics, especially when considering external flow problems such as aerodynamics (G. Tschirschnitz, 2020). However, it can be more time consuming than other method, and there are many fluid issues that it cannot be applied to – although it may produce inaccurate results if attempts are made to solve these via FEM solvers.

The Finite Volume Method is the most widely used in CFD, as its reliance on subdivision of volume lend itself naturally to fluid calculations' use of volume. In this method, each smaller volume transfers the fluid flows to its neighbouring volumes. They can support grids of any geometry, which is helpful when considering flow around a complex surface, but they can

come with a higher computational cost than other methods (N. Ashgriz, 2004). This is the method that would be most applicable to development work on the paddle blade, due to its complex curvature.

Many other solvers are in use in situations where they attain more accurate results, such as the Spectral Method, Lattice Boltzmann Method, and more modern developments such as Smooth Particle Hydrodynamic are further expanding the capabilities of CFD (G. Tschirschnitz, 2020). There are also many turbulence models, the selection of which will generate different results so requires careful understanding before solving takes place.

6 Experimental Approach to Model Validation

As discussed previously, there are many ways that a simulation can produce results that may seem valid, but in reality are inaccurate. As these programmes derive results analytically, the errors are never in the calculations, but always user error at the pre-programming stage, often due to shortcomings in knowledge or misinterpretation of the dynamics of a scenario. To ensure these errors don't affect the final design, any simulations must be validated. This can be done either by introducing boundary conditions with known results, or by running an experiment with the aim of correlating the simulation to real world results.

The most convenient method to attempt to validate results would be to fit the blade with relevant instrumentation, then use in in a real-world situation; but as Leroyer (2008) states, this approach would not be sufficiently repeatable to build or validate models. Their chosen approach was to use the same solver and conditions on a simplified blade, then run experiments on this simplified blade to validate it, before running further simulations on more complex geometry without the need for later validation. While this approach is sufficient, it does assume that the solver will still be accurate beyond the tested conditions, and there is a chance this may not be true. As such, the proposed method of testing a prototype of proper geometry would ensure accuracy without the need for this assumption.

To validate the model, specific values must be taken for parameters that can conveniently be tested experimentally. Sumner (2003) did this in a wind tunnel by testing the Drag and Lift forces acting on the blade, through the use of a force balance. Instead of running the experiment in water, which would have involved equipment which would be harder to attain and set up, the air velocity was increased by the necessary factor until the Reynolds Number was equal to that of equivalent conditions in water. Pitot-Static tubes were used to measure air velocity near the blade. The forces attained from this experiment could be compared to the CFD model's given values for pressure exerted on the blade, to validate the model.

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