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Designing a Tanker Propeller

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Abstract

Design can be complicated, requiring foundational knowledge around the subject area the design is based. Marine propellers require knowledge of fluid mechanics to mitigate any negative effects from fluid characteristics, whilst utilising them for gain.

This report found that there are many considerations, particularly around Reynolds Number which is effectively utilised to understand fluid characteristics. Propeller blades like other surfaces in fluid dynamics have a boundary layer which is a thin layer of fluid over the contacting surface, which is subjected to shearing forces. Boundary layer thickness is determined by fluid viscosity. If inertial forces are too great compared to the viscosity, turbulent fluid flow occurs, affecting a propeller's ability to perform effectively.

Propeller design is thus vital for controlling the boundary layer for particular operations, therefore, various designs under certain conditions may cause boundary layer complications such as increased thickness, separation, or high stagnation points, which may have detrimental effects on the operation due to energy conservation laws.

Material selection for propellers can also influence propeller performance. Carbon Fibre Reinforced Plastic has many advantages due to its advanced properties, such as its' strength to weight ratio, and high fatigue strength. Conversely, it is still under development due to more testing requirements around material water ingress causing losses in strength, as well as manufacturing being complicated, thus, increasing costs, whilst also leading to possibilities of cavitation erosion. Although new developments around additive manufacturing are leading to promising lost-cost manufacturing, however, they are currently only capable of low-volume manufacturing.

Computational methods have been developed which have allowed fluid analysis to become more efficient and accurate. However, an understanding of various types and their merits and limitations is required for appropriate implementation.

Experimental analysis can be completed to gain a realistic understanding of fluid behaviour. Cavitation tunnels are very efficient experimental methods, allowing for high accuracy due to their capability of controlling many boundary conditions, whilst allowing for many various measurements to be taken. Having understood the fluid characteristics and quantifying them, one can compare these to the computational methods for further reassurance.

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1.0. Introduction

Design is complex; thus, requires foundational knowledge to apply theories to the design, producing efficient, reliable products.

1.1. Report Purpose

This report investigates fluid mechanic theories to design a marine propeller. It will state the theories that apply to propeller design, whilst outlining various material considerations, and further describing simulation techniques whilst comparing them to a suggested experimental method, ensuring optimal knowledge.

2.0. Task One – Reynolds Number

2.1. Reynolds Number Definition

Reynolds number (Re) introduced by Sir George Stokes in 1851, was made popular by Osborne Reynolds in 1883 and given its' name in 1908 by Arnold Sommerfeld. Re is a dimensionless number interpreted as a ratio of inertial forces to viscous forces. It is utilised to categorise fluid systems; thus, the viscosity effect is important in controlling the velocities and patterns of fluid flow (Uruba 2018, p.1).

Re is defined with the formula:

$$Re = \frac{\rho \cdot u \cdot L}{\mu} = \frac{u \cdot L}{\nu} = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{\text{Fluid and Flow Properties}}{\text{Fluid Properties}}$$

Table 1. Re Variable Description

Re	Reynolds Number
ρ	Fluid Density
u	Fluid Velocity
L	Significant Length
μ	Dynamic Viscosity
ν	Kinematic Viscosity

These definitions are further supported by Gilbert-Kawai, Wittenberg, Davies and Gilbert (2014, pp.21-23) whereby it is stated Re determines whether flow is laminar (Ordinally fluid flow) or turbulent (Chaotic fluid flow).

Critical Re between laminar and turbulent flow is the point of transition, known as transient flow, thus, containing both characteristics. Typical values stated by Yousefi and Razeghi (2018, p.2) shown in table 2 can however vary if flowing over curvatures.

Table 2. Re Values for Each Fluid State

Surface	Reynolds Number	Fluid State
Internal Flow	$Re < 2300$	Laminar
Internal Flow	$2300 < Re < 4000$	Transient
Internal Flow	$Re > 4000$	Turbulent
External Flow (Flat)	$Re < 5 \cdot 10^5$	Laminar
External Flow (Flat)	$5 \cdot 10^5 < Re < 3 \cdot 10^6$	Transient
External Flow (Flat)	$Re > 3 \cdot 10^6$	Turbulent

2.2. Reynolds Number Importance and its' Propeller Fluid Flow Effects

Re is vital for operational purposes as it determines fluid flow characteristics over or through objects. Bernoulli's Equation involves energy conservation, whereby a velocity increase decreases pressure and vice versa. Increasing fluid flow velocity over a propeller blade's front face will decrease pressure, whilst maintaining or increasing rear blade pressure from reduced velocity or turbulent fluid, will create pressure differentials, creating lift for propulsion. Thus, understanding Re is vital for minimising unwanted turbulence in areas negatively affecting propulsion (Marciotto, 2016, pp.1-5).

Re variables can be manipulated, such as aircraft flying at high altitudes, reducing density, whilst maintaining velocity, thus, maintaining Re values, and reducing turbulent flow over aerofoils. Re varies over marine propeller blade regions. As the fluid travels from leading to trailing edge, Re increases due to significant length increase, thus, laminar to turbulent flow occurs as figure 1 shows (Yousefi and Razeghi, 2018, p.2).

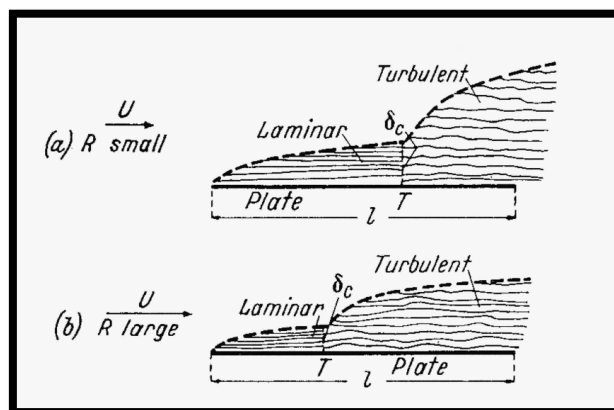


Figure 1. Laminar to Turbulent Flow (Eckert, 2018)

Figure 2 also shows these fluid characteristics, with the tip having turbulent flow from leading to trailing edge due to centrifugal forces accelerating the fluid, as well as tip speed being greater due to the furthest distance from a rotating masses central point needing to travel further, thus, having greater linear velocity, hence a higher Re at the tip compared to the root (Earley, 2013).

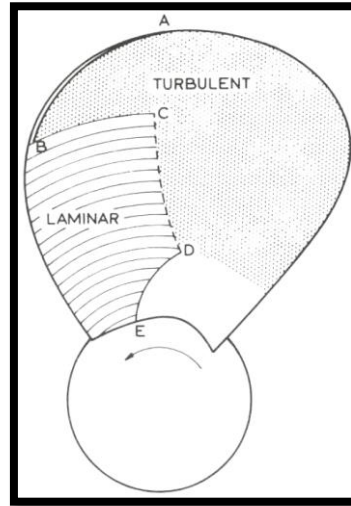
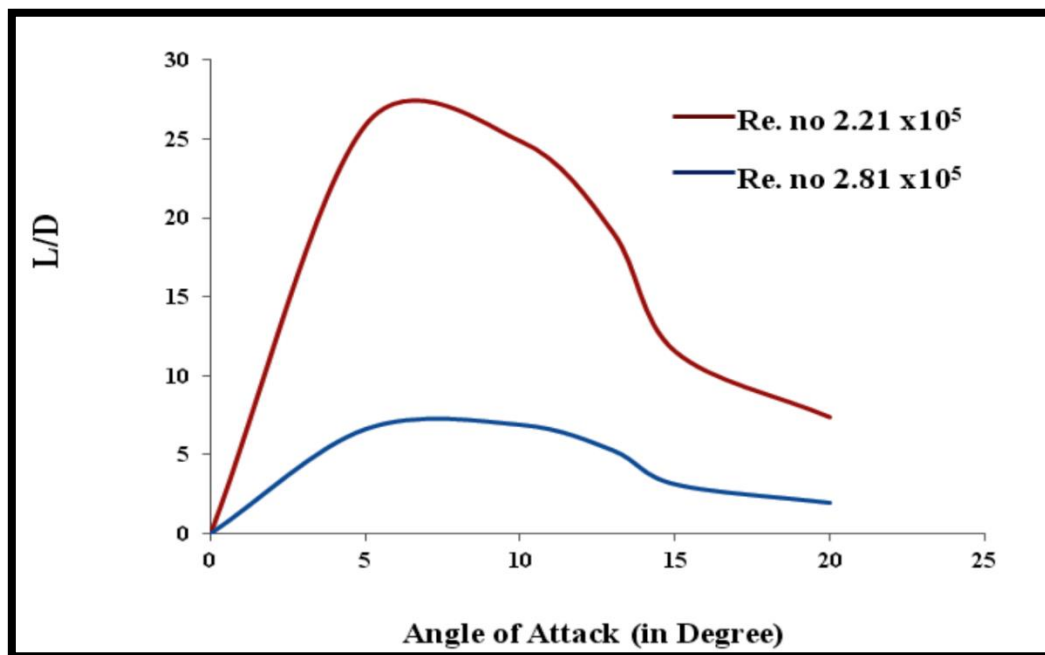


Figure 2. Fluid State Over a Propeller-Blade (Baltazar, Melo and Rijpkema, 2020).

Understanding Re is critical for operational optimisation, allowing one to quantify the condition of fluid around objects, thus, understanding the events that will follow for the given fluid characteristics. This depends on the object, as graph 1 shows the Re effect on lift at various conditions for aerofoils.



Graph 1. Various Angle of Attacks for Two Re (Jha, Gautam, Narayanan and Kumaraswami Dhas, 2018)

2.3. Reynolds Number Estimation

The Re calculation requires values, with blade length obtained from figure 3. Assumptions are shown in table 3 with values from Seawater–Properties (2022) based on the assumptions shown in table 4.

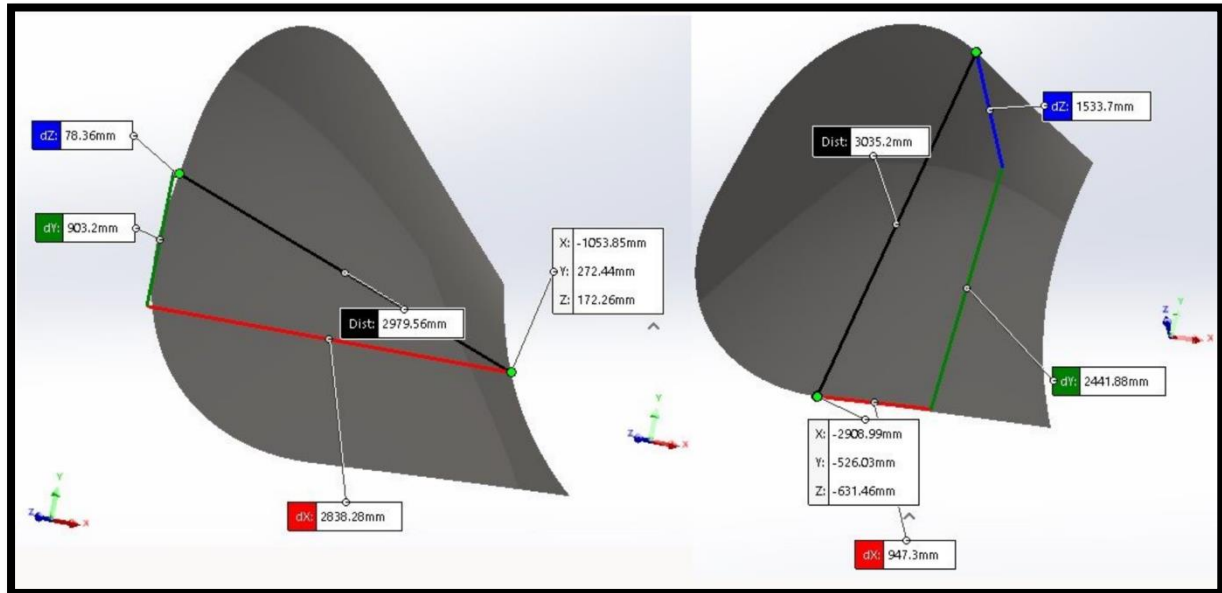


Figure 3. Blade Dimensions

Table 3. Propeller Performance Assumptions

Assumptions
Propeller is operating in seawater at 10°C
Propeller Revolutions Per Minute (RPM) are: 80
Water is calm with no external disturbances from upstream flow
Blade propellers have zero deflection
Blade propellers have zero vibration
Surface Roughness and Temperature are negligible

Table 4. Re Variables

Variables	
Salt Water Density at 10°C	$\rho = 1027 \text{ kg/m}^3$
Salt Water Dynamic Viscosity	$\mu = 0.00141 \text{ kg/m} \cdot \text{s}$
Significant length for plates utilises length perpendicular to flow, determining Re for Body drag, parallel to flow to determine Re for Lift and Drag or Drag Friction. However, analysing the entire propeller, not just a blade, means considering it as a single body, thus, the diameter must be utilised with the Re calculation altered for this compensation (Reynolds number Re, 2021).	<i>Blade Length = 2.98 m (Two Decimal Places)</i> $\therefore \text{Radius} = 2.98 \text{ m}$ $\therefore \text{Diameter} = 5.96 \text{ m}$

Re calculation is:

$$Re = \frac{\rho \cdot u \cdot L}{\mu}$$

However, adjusting the equation for a single body, means that the entire propeller is taken into consideration, for a more accurate result, therefore:

$$Re = \frac{\rho \cdot \left(\frac{RPM}{60}\right) \cdot d^2}{\mu}$$

$$\therefore Re = \frac{1027 \cdot \left(\frac{80}{60}\right) \cdot 5.96^2}{0.00141}$$

$$Re \approx 34.5 \cdot 10^6 \text{ (One Decimal Place)}$$

If one wanted to find Re over a single blade, one could convert RPM into linear velocity as follows:

$$\text{Blade Length} = 3.04 \text{ m (Two Decimal Places)}$$

$$Re = \frac{\rho \cdot u \cdot L}{\mu}$$

$$\therefore \omega = \frac{RPM}{60} \cdot 2\pi$$

$$\omega = \frac{80}{60} \cdot 2\pi$$

$$\omega = 8.38 \text{ Rad/s (Two Decimal Places)}$$

$$\therefore u = \omega \cdot r$$

$$u = 8.38 \cdot 3.035$$

$$u = 25.14 \text{ m/s}$$

$$\therefore Re = \frac{1027 \cdot 25.14 \cdot 3}{0.00141}$$

$$Re \approx 54.93 \cdot 10^6 \text{ (Two Decimal Places)}$$

One can see the answers are different. Firstly, the second Re calculation utilises parallel flow over the blade as one is trying to find Re over the blade, not the entire propeller. Secondly, fluid flow over a blade does not act precisely parallel to the blade due to the rotation and propeller design.

Furthermore, results may vary due to the simple calculations used to convert RPM to linear velocity. However, although both Re calculations are approximations with the first being the most accurate, they do not account for other variables, such as propeller pitch, water cavitation, propeller slip, curvatures and surface roughness (Yousefi and Razeghi, 2018, p.2).

3.0. Task Two – Boundary Layer and Design

3.1. Boundary Layer and its' Flow around a Propeller

Boundary layers being thin layers of fluid over a contacting surface are subjected to shearing forces, with thickness, described in table 5, is determined by viscosity. On a propeller surface velocity is zero, known as the zero-slip condition, however, velocity monotonically increases with distance from the surface, until reaching free-stream velocity (Augustyn, 2020).

Table 5. Boundary Layer Thickness Definitions

Boundary Thickness	Boundary layer thickness increases the more viscous a fluid, as the greater friction causes a greater flow resistance, thus, a further distance until the fluid flow reaches the free-stream velocity. This is the thickness that will affect the propeller blade. It is the point normal to the surface having reached 99% of free stream velocity (Shalmali, 2021).
Momentum Thickness	The distance which the total loss of momentum per second is equal to that if the fluid were passing a stationary propeller blade (Shalmali, 2021).
Energy Thickness	The distance measured perpendicular to the propeller blade solid body, which the boundary should be displaced, compensating for a reduction in kinetic energy of fluid flow, due to boundary layer formation (Energy Thickness in Boundary Layer, 2022).
Displacement Thickness	The distance is measured perpendicular to that of the boundary in which the free stream is displaced on account of the formation boundary layer (Shalmali, 2021).

Furthermore, a marine propeller, for example, will have a larger boundary layer compared to an aircraft propeller for a given speed, due to water being more viscous than air. On a surface like that of the propeller, Re increases from leading to trailing edge, producing a thicker boundary layer towards the trailing edge, as turbulent fluid flow has a different velocity profile compared to laminar, due to Eddie Currents, causing a resistance to flow, thus, increasing pressure and thus friction, causing a thicker boundary layer as shown by figure 4 (Baltazar, Melo and Rijpkema, 2020, p.2).

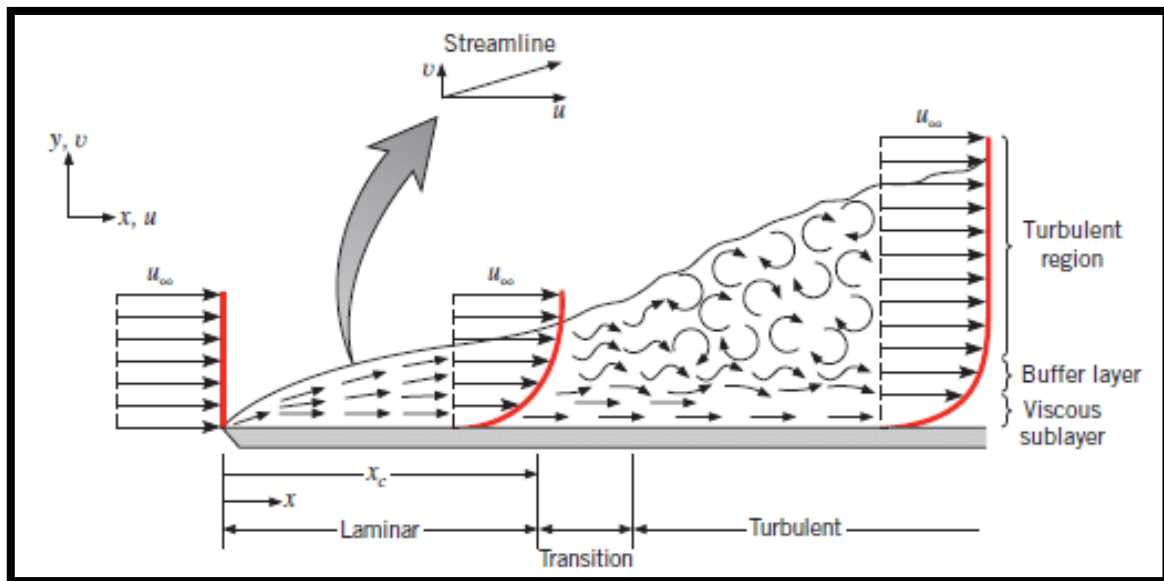


Figure 4. Boundary Layer Characteristics (Hussein and El, 2018)

3.2. Propeller Design and Further Boundary Layer Flow

Boundary layer control is vital for propeller operation. Propellers work on the principle of pressure differentials and Newton's Third Law. They are designed to create low pressure on the front face (Suction side) and high pressure on the rear face (Pressure side) shown in figure 5.

Some propellers achieve this with a screwing effect, due to propeller pitch, drawing fluid from the front and expelling it rearwards, thus, low pressure on the front face occurs, causing propulsion. Furthermore, the force produced from drawing and expelling the fluid, creates an equal and opposite forward force, providing further propulsion. Some propellers also achieve pressure differential propulsion by having aerofoil designed propeller blades, which accelerate fluid over the front face blades decreasing the pressure due to conservation laws stated within

Bernoulli's equation, whilst maintaining or increasing pressure at the rear, therefore, providing lift, thus, propulsion (Carlton, 2007, pp.31-50).

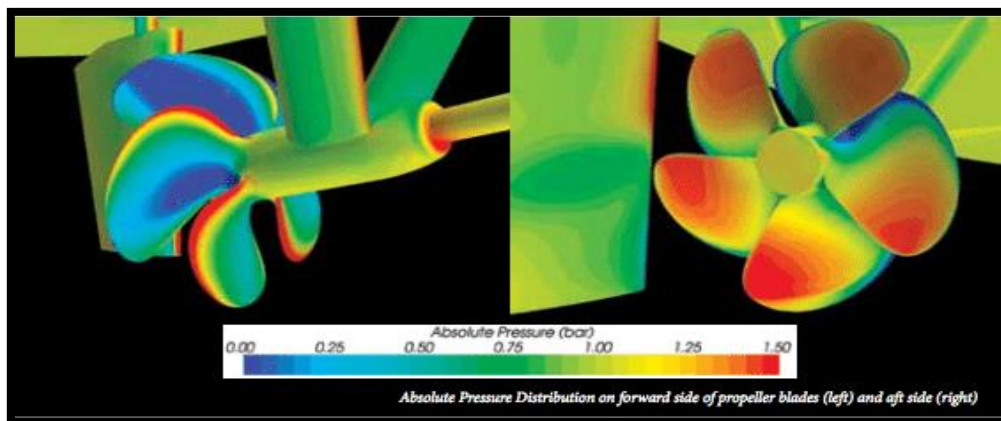


Figure 5. Propeller Pressure Differentials (Stockdill, 2012)

Without Re variable control, the turbulent flow would disrupt the boundary layer reducing propeller efficiency. As the boundary layer would be greater at the tip, due to tip speed, a blade twist from root to tip would ensure a constant angle of attack relative to fluid flow like the proposed design. However, an improvement to the design as figure 6 shows, would be curving the propeller from root to tip altering fluid vector direction and reducing linear velocity, thus, reducing Re to maintain boundary layer behaviour. However, this also increases fluid travel length, thus, shortening the leading to trailing edge tip, would further help control fluid characteristics (Carlton, 2007, pp.31-50).

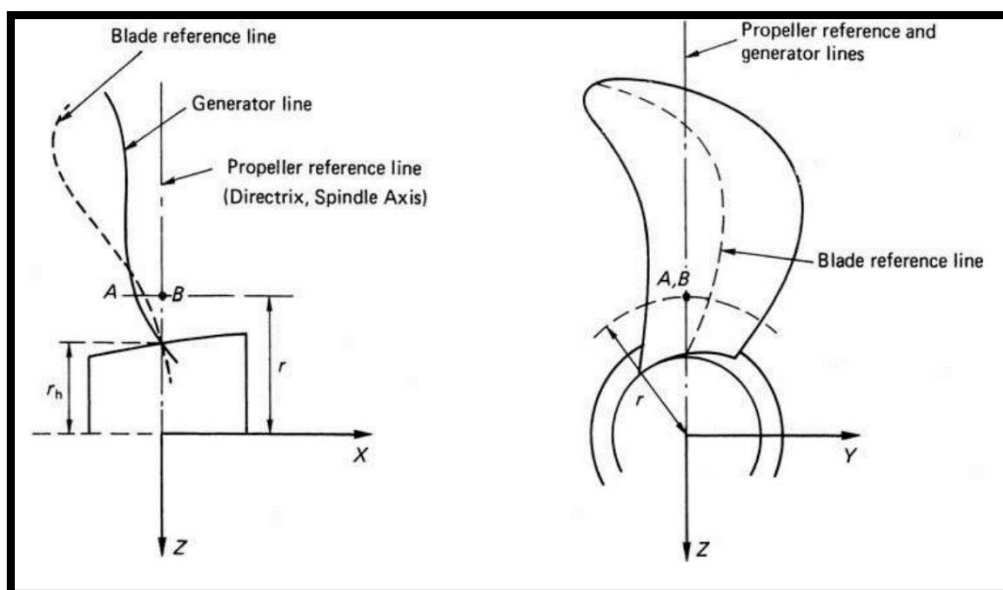


Figure 6. Blade Geometry (Carlton, 2007).

Interestingly, figure 7 shows high pressure at the leading edge, this is due to the stagnation point, whereby fluid has zero velocity. Hence leading edges must be thin, reducing this effect (Carlton, 2007, p.146).

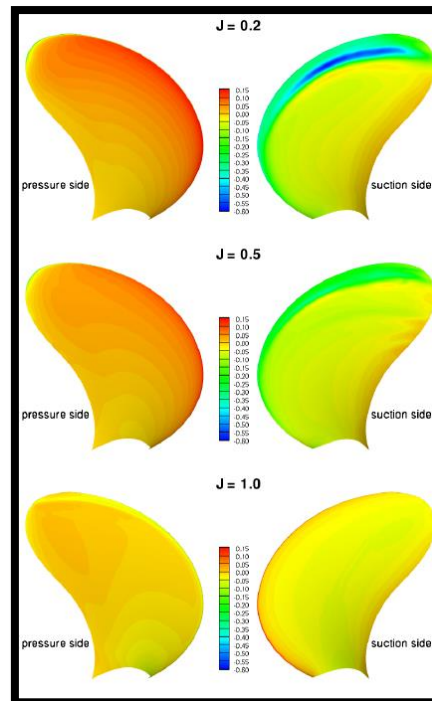


Figure 7. Blade Pressure Differentials (Muscari and Di Mascio, 2009)

Boundary Layers have low energy relative to free stream velocity, therefore, is driven by pressure changes, hence, fluid velocity is unable to resist inertial forces preventing fluid from following high curvature surfaces. This indicates that inertial forces are greater than viscous forces, hence, Re is high, therefore, boundary separation occurs with high turbulent flow (Winslow, Otsuka, Govindarajan and Chopra, 2018, pp.1050-1051).

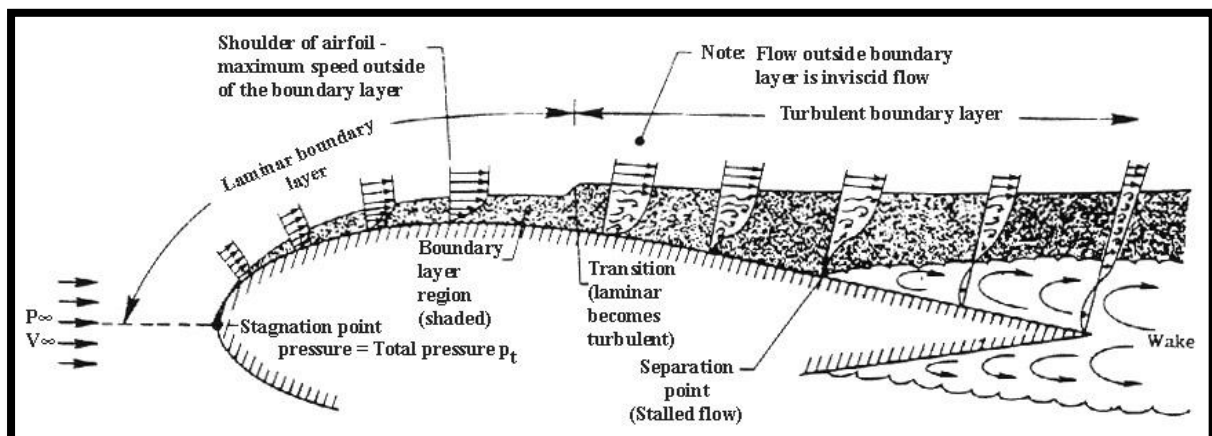


Figure 8. Boundary Layer Separation (Khan, 2019)

To reduce this effect, curvatures must be kept to an optimum range for that fluid. Marine propellers may have higher curvatures than aircraft propellers, as water is more viscous, therefore, able to resist larger inertial forces. Optimum curvatures can ensure benefits at higher Re as figure 9 shows.

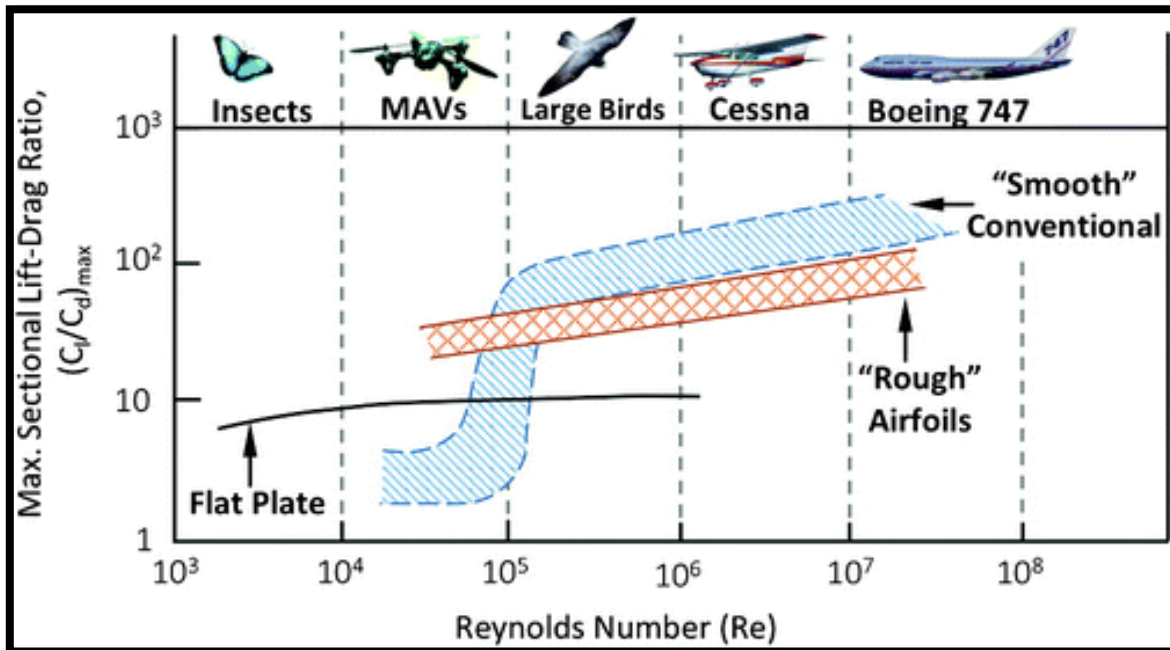


Figure 9. Curve Effect on Lift (Winslow, Otsuka, Govindarajan and Chopra, 2018)

Increasing the number of propeller blades reduces vibrations, increasing stability, thus, power and load capability. However, fewer blades are more efficient, but vibrations are too severe. To reduce vibration further, increasing the length generates the same Re at lower velocities, whilst maintaining similar propulsion (Kuznetsov, 2022).

Length increase also reduces cavitation caused by low pressure on the suction side, causing vapour bubbles through boiling, which reduces efficiency. This can be further reduced by increasing torque by varying propeller pitch, explained more in Appendix One (Carlton, 2007, pp.207-212).

4.0. Task Three – Proposed Propeller Material

4.1. Carbon Fibre Reinforced Plastic

Carbon Fibre Reinforced Plastic (CFRP) material consists of a matrix, with synthetic resin and reinforcing carbon fibre. Carbon fibres have high strength to density ratios and high stiffness, whilst maintaining structural integrity up to 3000°C. CFRP also have high fatigue strength and dimensional stability (Ozkan, Gok and Karaoglanli 2020, p.238).

A Brief History of Carbon Fibre (2019), wrote an article stating CFRP has advanced mechanical properties due to current manufacturing processes, with earlier developments of composites having higher manufacturing costs, and did not lead to the same property results of today.

Historically, earlier composite filaments were cotton or bamboo. The article goes on to say in 1958 petroleum-based carbon fibres were accidentally produced and it wasn't until 1960 that Dr Akio Shindo produced a cost-effective method to make carbon fibre of 55% carbon. Today, the development of 95% carbon exists with advanced properties and advanced manufacturing processes.

4.2. CFRP for Propellers

Pegorari (2018) states CFRP is under continuous development across industries due to its' high strength, high stiffness and ease of complex shape manufacture, thus, stating the great potential for marine propellers, such as reduced blade deflection from high stiffness properties, reducing energy losses and transmission stress, thus, improving efficiency. Furthermore, historically and currently, Nickel Aluminium Bronze (NAB) alloy propeller blades are one of many materials used, which can be susceptible to corrosion if their oxide layer is damaged, causing structural concerns, and increasing the chances of turbulent fluid flow and boundary layer separation, preventing the propeller from performing effectively.

Bird and Ross (2012, p.186) state friction coefficients influence fluid dynamics, with Kumar, Krishna and Subramanian (2018, p.1) stating composites are not susceptible to corrosion, thus, reducing maintenance costs and friction coefficient alteration. Table 6 shows historical propeller blade material properties compared to CFRP.

Table 6. Propeller Material Properties (Kumar, Krishna and Subramanian 2018)

MATERIAL PROPERTIES	CARBON FIBRE (Unidirectional)	ALUMINIUM ALLOY	NICKEL ALUMINIUM BRONZE	MANGANESE BRONZE
Youngs modulus (GPa)	120-220	68-72	122-130	110-120
Tensile strength (MPa)	800-1500	270-330	550-660	410-490
Density (gm/cm ³)	1.35-1.85	2.65	7.55	8.22
Thermal Conductivity (W/m.K)	20	117	42	80
Low coefficient of Thermal Expansion x10 ⁻⁶ (Inch/inch degree Fahrenheit)	-1 to 8	7-13	9	12
Poisson ratio	0.27	0.33	0.32	0.34

Propeller blades must follow regional regulations. These can be set out by the International Organisation for Standardisation (ISO) for maritime standards. Under the Rules for Classification, regarding propulsion systems, one can find material regulations shown in table 7, of which each material is considered case-by-case. There are no regulations regarding CFRP as of yet, however, the properties would likely be approved for a marine propeller, due to them exceeding that of all the other materials' requirements (DNV 2015, p.12).

Table 7. Material Property Requirements (DNV, 2015)

Material	Material constant U_1 [N/mm ²]	Material constant U_2 [-]	Minimum yield strength σ_y [N/mm ²]	Minimum tensile strength σ_B [N/mm ²]
Mn-Bronze, CU1 (High tensile brass)	55	0.15	175	440
Mn-Ni-Bronze, CU2 (High tensile brass)	55	0.15	175	520
Ni-Al-Bronze, CU3	80	0.18	245	590
Mn-Al-Bronze, CU4	75	0.18	275	630
Martensitic stainless steel (12Cr 1Ni)	60	0.20	440	590
Martensitic stainless steel (13Cr 4Ni/13Cr 6Ni)	65	0.20	550	750
Martensitic stainless steel (16Cr 5Ni)	70	0.20	540	760
Austenitic stainless steel (19Cr 10Ni)	55	0.23	180	440
Forged steel and other materials shall be especially considered.				

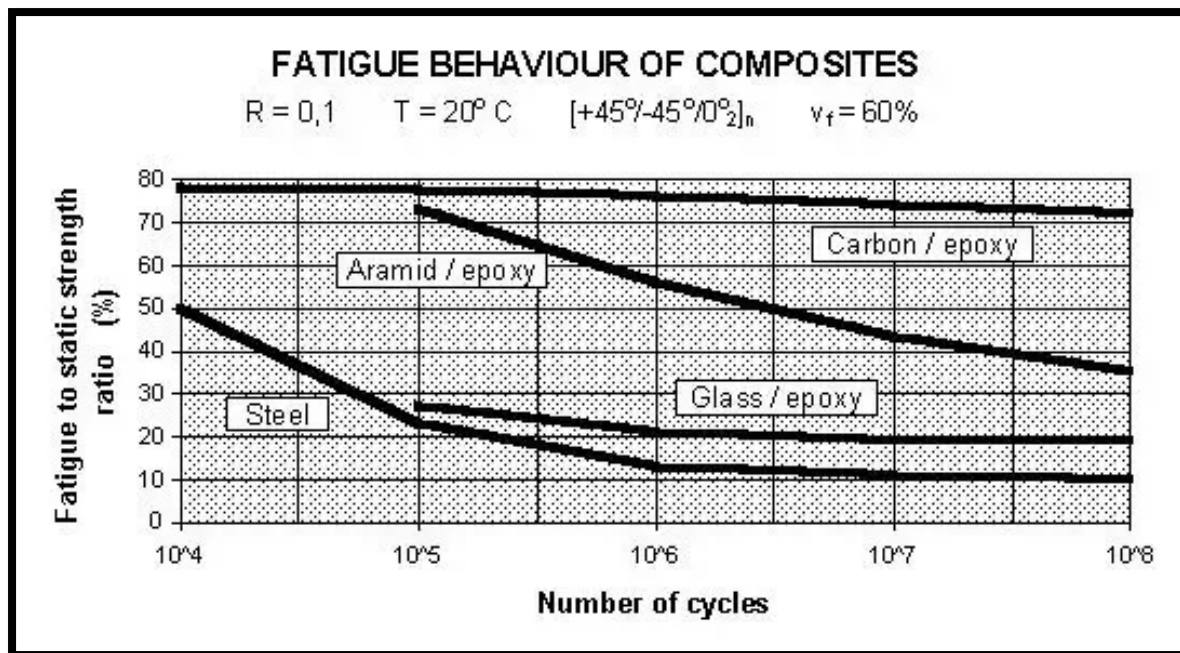
One main guidance note of the material is that it meets fatigue strength, withstanding at least 10^7 cyclic loading with a frequency no higher than 5hz, of which the calculation of the standards is:

$$U_1 = \frac{U_{E7}}{1.3} - 2 \cdot \sigma_{E7}$$

Table 8. Variable Descriptions

U_1	Fatigue Properties in Seawater
U_{E7}	Average Fatigue Amplitude (N/mm ²) up to 10^7 cycles with zero mean stress
σ_{E7}	Corresponding Standard Deviation (N/mm ²)

Therefore, within this regulation, one can state CFRP meet industry standards, having approximately 800-1500 MPa fatigue strength at 10^8 cycles, compared to materials like NAB with 255 MPa at 10^8 cycles which are compared in graph 2.



Graph 2. Material Fatigue Strength (Zaludek et al., 2020)

Therefore, CFRP, having advanced properties and potentially meeting industry standards would mean a viable material choice for propellers.

Conversely, although steadily reducing, manufacturing costs of CFRP are still high. However, current developments around additive manufacturing are occurring with 3D printers shown in figure 10, being able to produce carbon fibre layered with polymers (Shen et al., 2019, pp.1-7).

This would be advantageous for prototyping to understand fluid flow around a design, due to its ability to produce low cost, complex shapes. However, moulds would still need to be created for high-volume manufacturing, thus, further developments are required.



Figure 10. Carbon-Fibre 3D Printing (3D Printing Carbon Fiber and Other Composites, 2022)

Therefore, with CFRP properties, it seems a logical material choice, as it could withstand twisting and deformation, transferring more torque, whilst maintaining fluid characteristics.

Conversely, CFRP does not efficiently absorb energy, thus, foreign object damage may cause instant failure. Some composite materials break down with water ingress causing strength reduction by 50% when loaded perpendicular to the fibres, and worsened with elevated temperatures. Interestingly, no strength loss occurs when loaded parallel to the fibres (Ryan, Adam and Brown, 2009, pp.1-11).

Almudaihesh et al. (2021, pp.1-22) supported these statements with experimental results shown in figure 11. However, only polymers were tested, not CFRP. Banks et al. (2000) carried out research into non-destructive testing methods for CFRP water ingress, however, no actual CFRP testing was completed, thus, further research is required, specifically within saltwater.

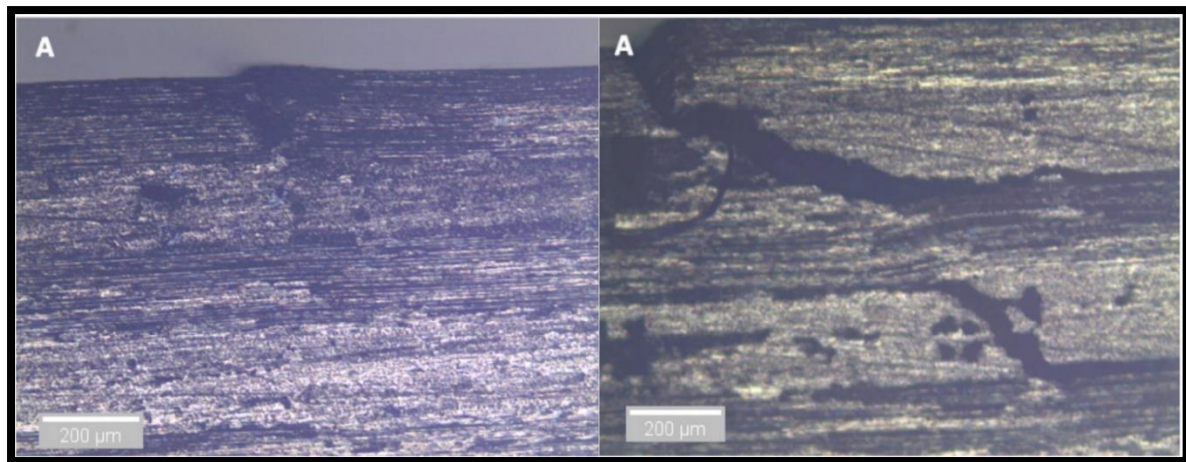


Figure 11. Polymer Structure loaded when Dry (Left) and Wet (Right)(Almudaihesh et al. (2021)

Furthermore, although resistant to corrosion, Yamatogi et al. (2022, p.10) state, CFRP are susceptible to cavitation erosion, whereby pockets of gas entire the resin during manufacture, causing surface deterioration and material loss shown in figure 12. This causes similar negative effects as corrosion.

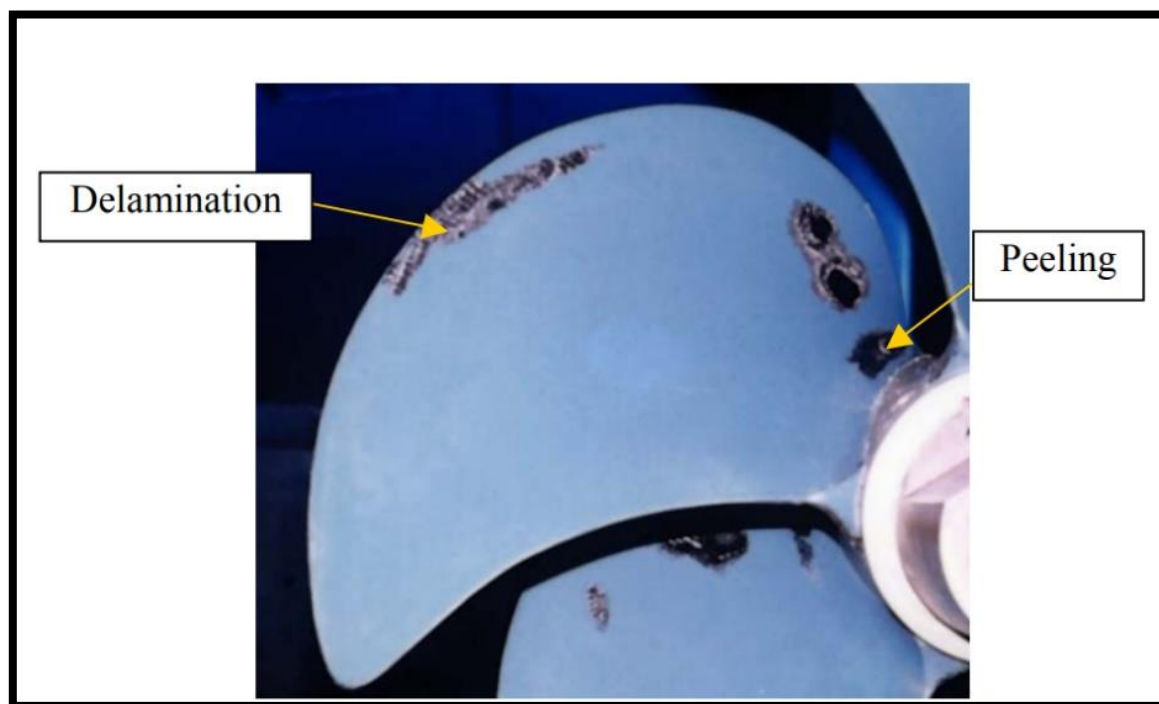


Figure 12. CFRP Cavitation Erosion Yamatogi et al. (2022)

Therefore, Pegorari (2018) is correct in saying the CFRP has potential. However, the material poses many problems with cavitation, decreased strength through water absorption and high-cost manufacturing issues. Therefore, further, development is required, which Nakaishma Co Ltd has been developing over the last decade, retrofitting CFRP propellers to ships to

understand their implications. Therefore, if the problems discussed were investigated further, CFRP would be an advantageous material for marine propellers, and thus, indicates the reasoning behind continuous CFRP propeller development (CFRP Propeller, 2022).

5.0. Task Four – Fluid Flow Modelling Techniques

Historically, analytical methods were used to solve fluid mechanic problems. Complicated problems made this harder, thus, Computational Fluid Dynamics (CFD) applying differential equations such as the Navier-Stokes Equations (NSE) are now utilised. A CFD simulation domain is shown in figure 13 (Carlton, 2007, pp.200-201).

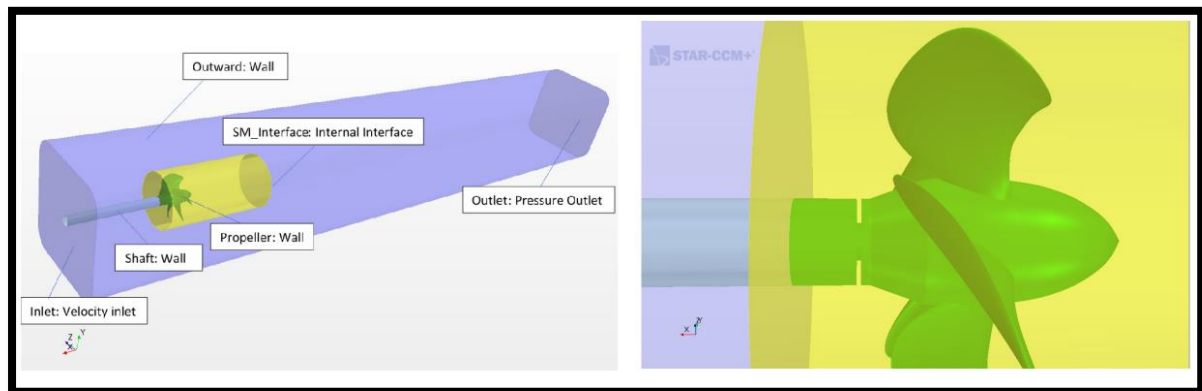


Figure 13. CFD Propeller Domain (Krasilnikov, 2022)

5.1. Computational Fluid Dynamics

NSEs within CFD are discretised and solved to understand fluid properties. CFD methods are categorised, with an Eulerian approach observing fluid from a standing point and a Lagrangian approach moving with the observed fluid as figure 14 shows (Tschirschnitz and Sabrowski, 2020).

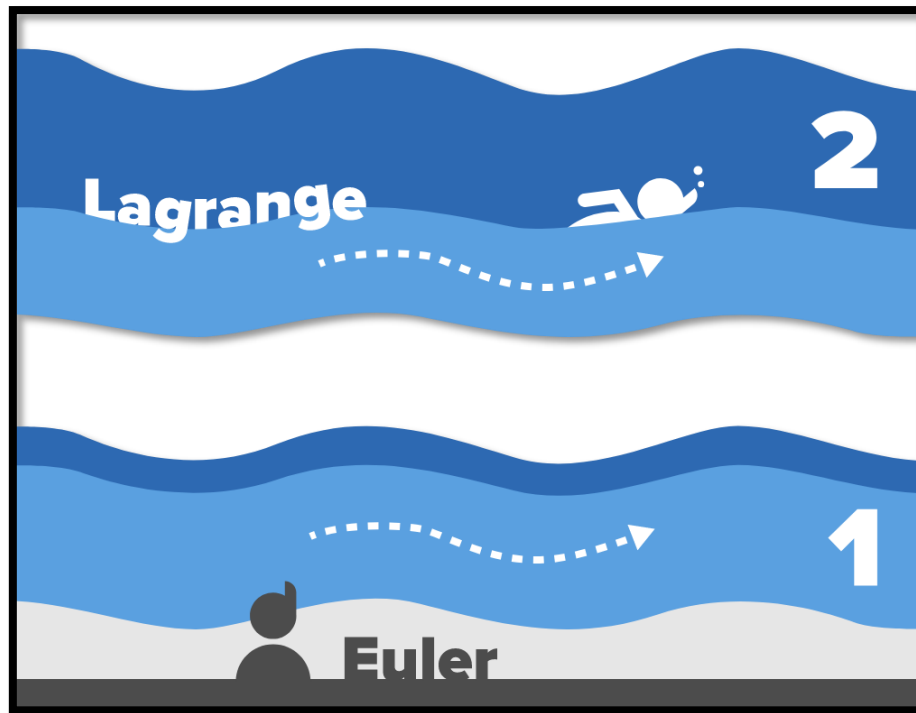


Figure 14. CFD Methods (Tschirschnitz and Sabrowski, 2020)

Eulerian methods use meshes, subdividing fluids into constant cells and then analysing the geometry. Lagrangian methods analyse points, known as particles, as they have mass, volume and velocity, which are free to move in space. These methods are broken down in figure 15 (Tschirschnitz and Sabrowski, 2020).

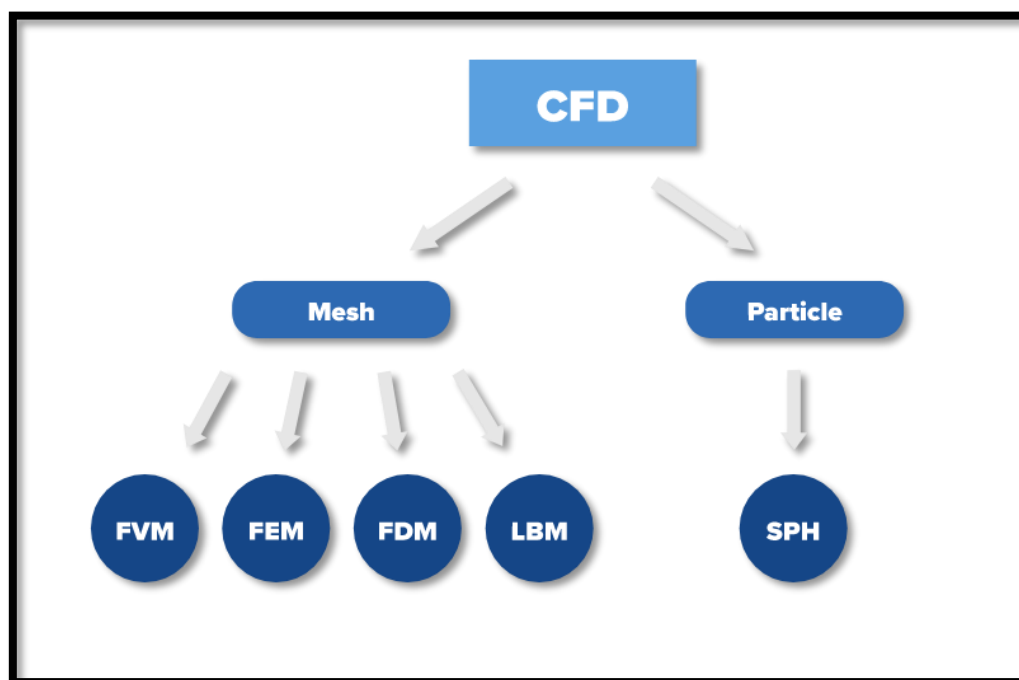


Figure 15. CFD Breakdown (Tschirschnitz and Sabrowski, 2020)

5.2. Mesh Analysis

For the simulation of a propeller, the Computer-Aided Design (CAD) file would be utilised, and a mesh of the geometry created, shown in figure 16.

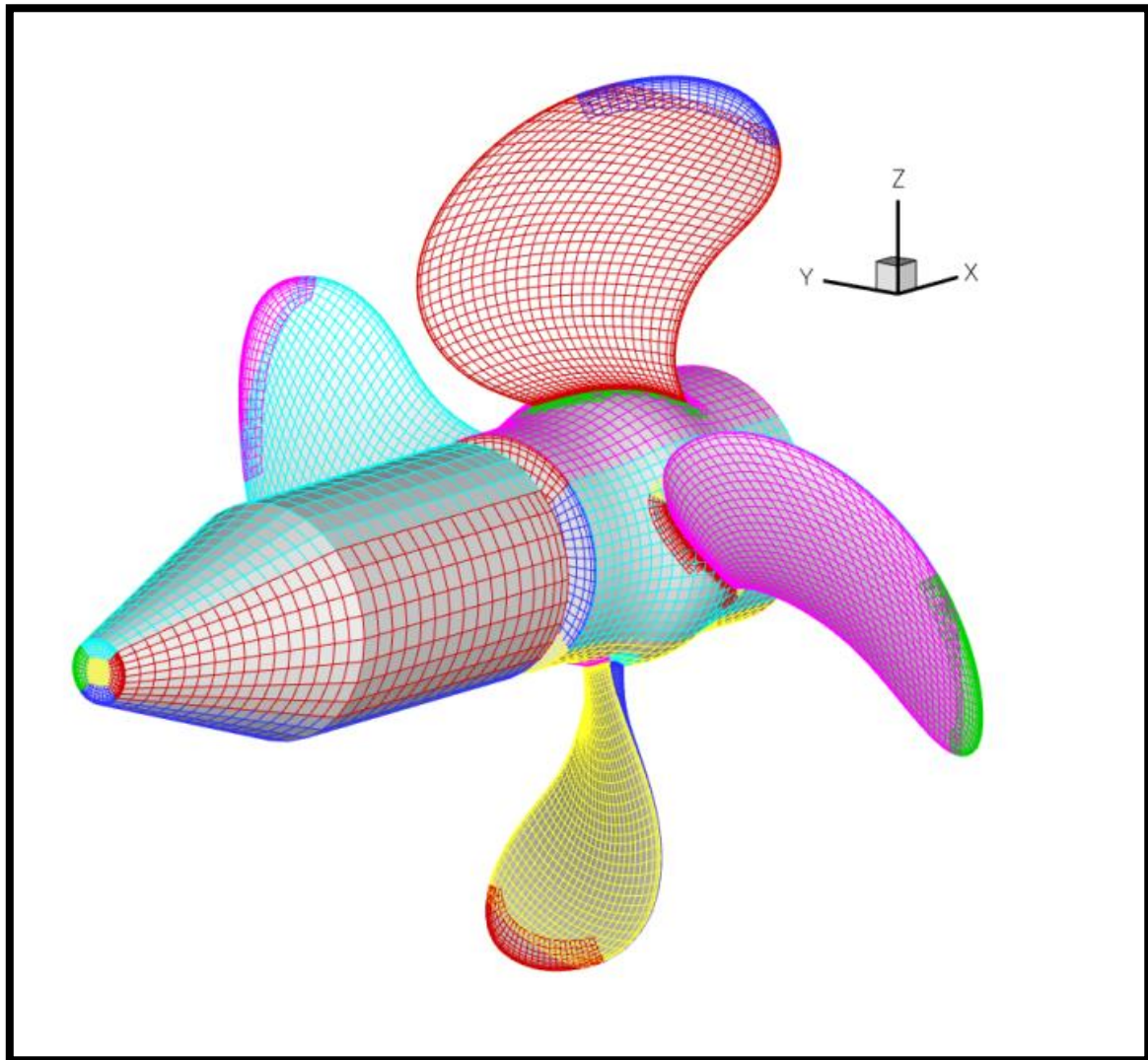


Figure 16. Propeller Mesh (Muscari and Di Mascio, 2009)

5.2.1. Finite Volume Method

Finite Volume Method (FVM) subdivides a whole domain into small control volumes. Conservation laws apply, thus, what enters a cell will leave the opposite side shown in figure 17. Flux conservation equations define an average sense over a cell by evaluating differential equations in the form of algebraic equations, thus, volume integrals in partial differential equations are converted to surface integrals using divergence theory (Eymard et al., 2010).

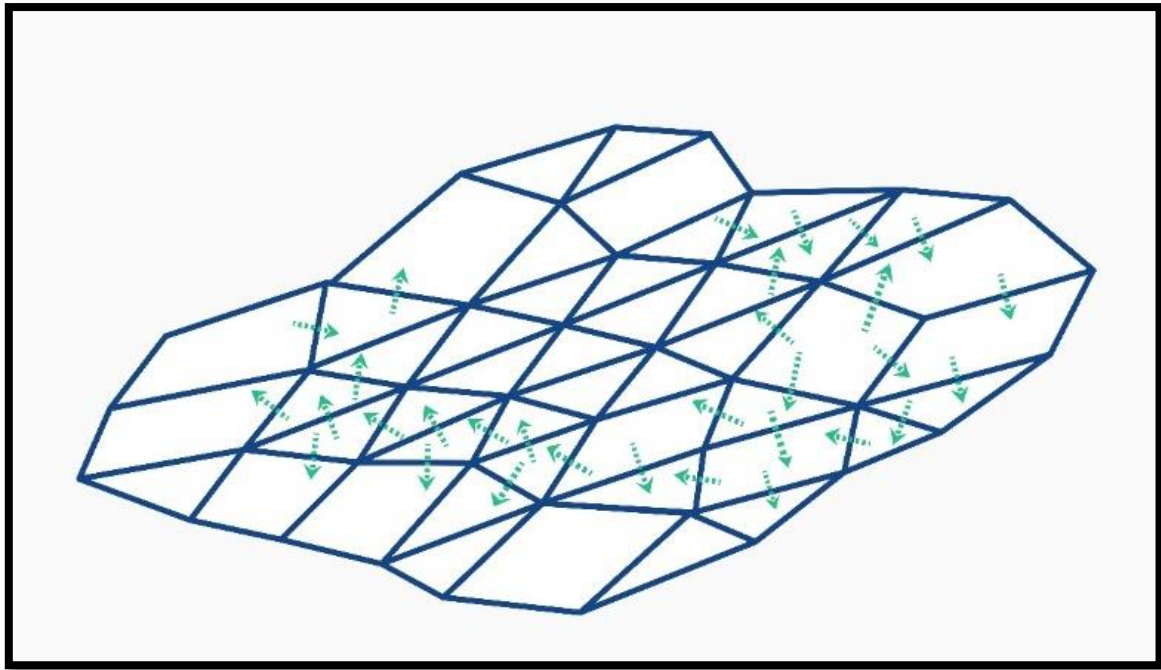


Figure 17. FVM Mesh (Tschirschnitz and Sabrowski, 2020)

FVM is advantageous as it only needs to do flux evaluations for cell boundaries, which remains for nonlinear problems. However, accuracy can be hindered as FVM cannot be easily made of higher-order, thus, more complex meshing techniques must be used, meaning programming and evaluation time increases (Sjodin, 2016).

5.2.2. Finite Element Method

Finite Element Method (FEM) subdivides space into very small finite elements, simplifying the shape and space. This shape would be like that shown in figure 16 with the space around it shown in figure 18.

Partial differential equations represent fluid flow within each element by approximating the fields within them as simple functions to give local discretise of the physics occurring. Each element's contribution is merged into a large representation matrix, which is computationally solved to understand the fluid flow (Sjodin, 2016).

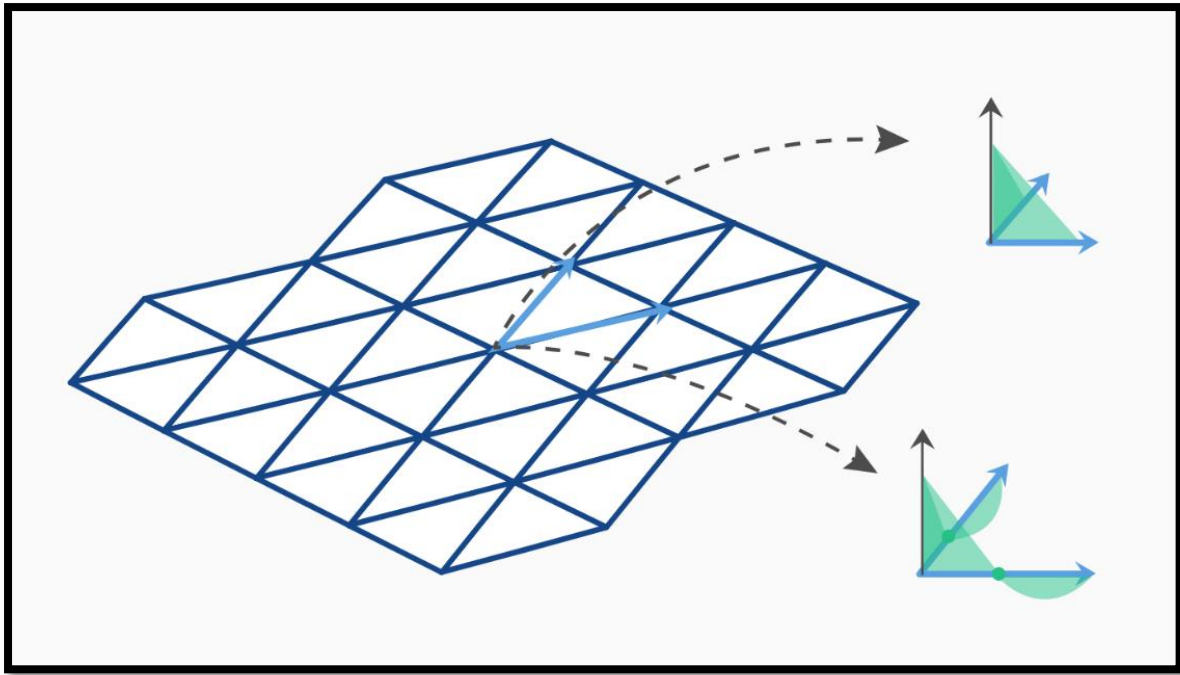


Figure 18. FEM Mesh (Tschirschnitz and Sabrowski, 2020)

FEM is advantageous due to its' adaptability for multiple applications. This means for the propeller simulation, various physical analyses can be applied at once, thus, understanding how different variables affect one another. Furthermore, unlike FVM, FEM can easily increase the order of elements, thus, increasing accuracy without added time.

Conversely, FEM is mathematically complicated and requires advanced expertise. Furthermore, time-dependant simulations require explicit solvers which is more complicated to achieve (Sjodin, 2016).

5.2.3. Finite Difference Method

Finite Difference Method (FDM) utilises simple block-shaped geometries representing the CAD model on a grid. This considers a point in space such as a point on the propeller, taking the continuum representation of the equations and replacing them with discrete equations known as finite-difference equations. Simply, it indicates the difference between the object and grid, shown in figure 19, to understand fluid behaviour (Tschirschnitz and Sabrowski, 2020).

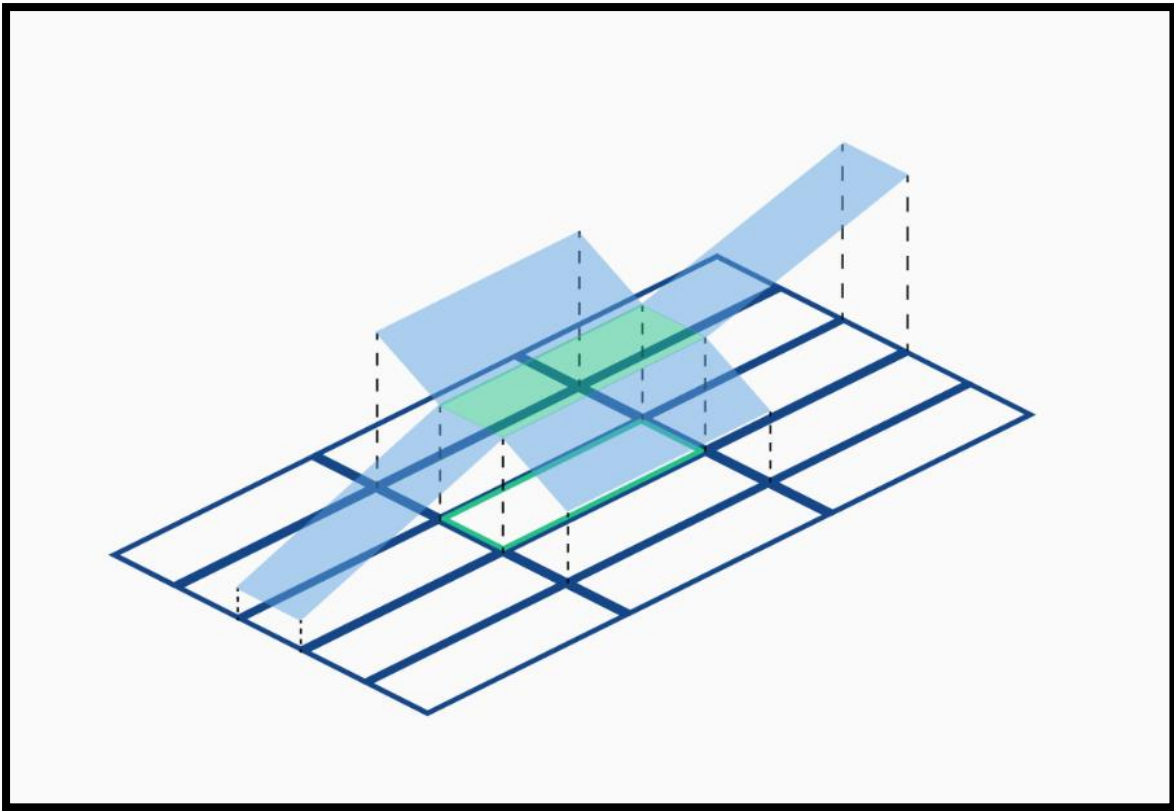


Figure 19. FDM Mesh (Tschirschnitz and Sabrowski, 2020)

FDM being defined as dimension per dimension means element order can be increased easily obtaining higher-order accuracy. This method is thus, one of the fastest and most efficient for simple shapes.

Conversely, with complex shapes like a propeller, low accuracy would occur due to it using simple geometry, thus, extra time spent developing complex boundary fitted meshes would be needed (Sjodin, 2016).

5.2.4. Lattice Boltzmann Method

Lattice Boltzmann Method (LBM) utilises the Boltzmann Equation, not NSE. A lattice mesh is generated seen in figure 20, with each cell exchanging mesoscopic shock events of fictitious particles with the next cell. Collisions and new mesoscopic quantities are computed based on the previously streamed particles. Thus, fluid properties like pressure, density and velocity are computed from the mesoscopic quantities (Tschirschnitz and Sabrowski, 2020).

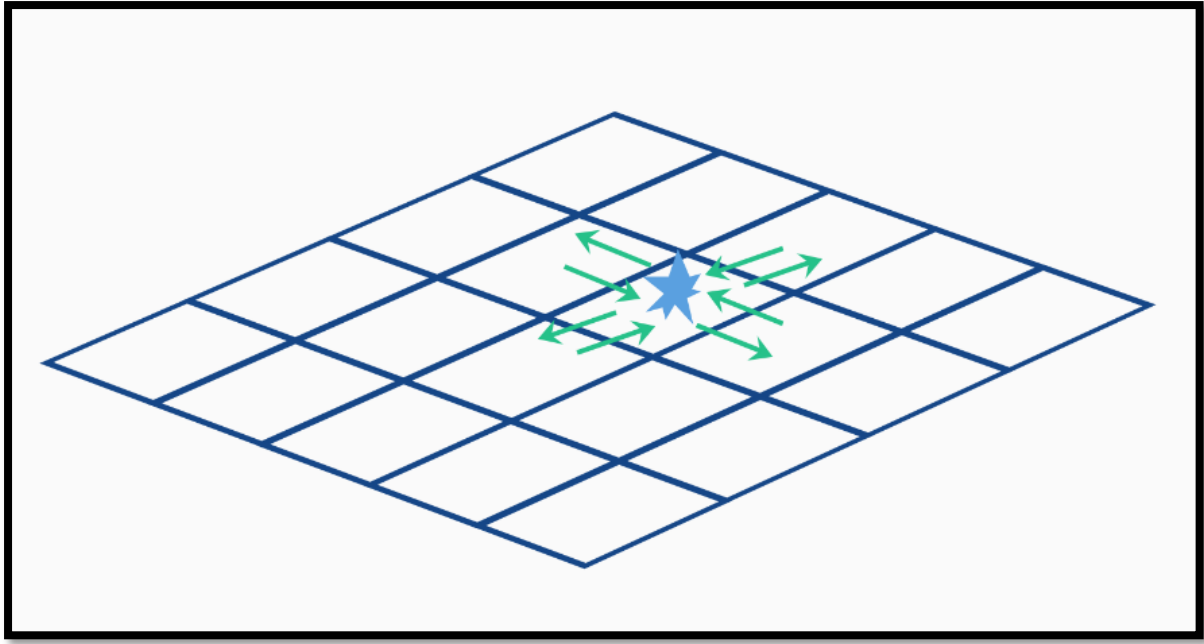


Figure 20. LBM Mesh (Tschirschnitz and Sabrowski, 2020)

Utilising Boltzmann equations ensures simpler boundary conditions, thus, easier implementation. This method also incorporates physics as standard; thus, body force interaction is accounted for without further programming effort.

Conversely, it is limited to square lattices, reducing accuracy, whilst having stability limitations of high-speed fluids (Tschirschnitz and Sabrowski, 2020).

5.3. Particle Analysis

The particle method utilises the Lagrangian method, thus, no meshes are used. The method used for this type is the Smoothed Particle Hydrodynamics (SPH) method (Tschirschnitz and Sabrowski, 2020).

5.3.1. Smoothed Particle Hydrodynamics

SPH shown in figure 21, discretises NSE, by analysing free-moving fluid following particles based on their velocity. Physical quantity derivatives are approximated by measuring the weight of neighbouring particles thus, determining their physical quantities. Kernel functions are utilised to calculate weighting for overall computational results (Tschirschnitz and Sabrowski, 2020).

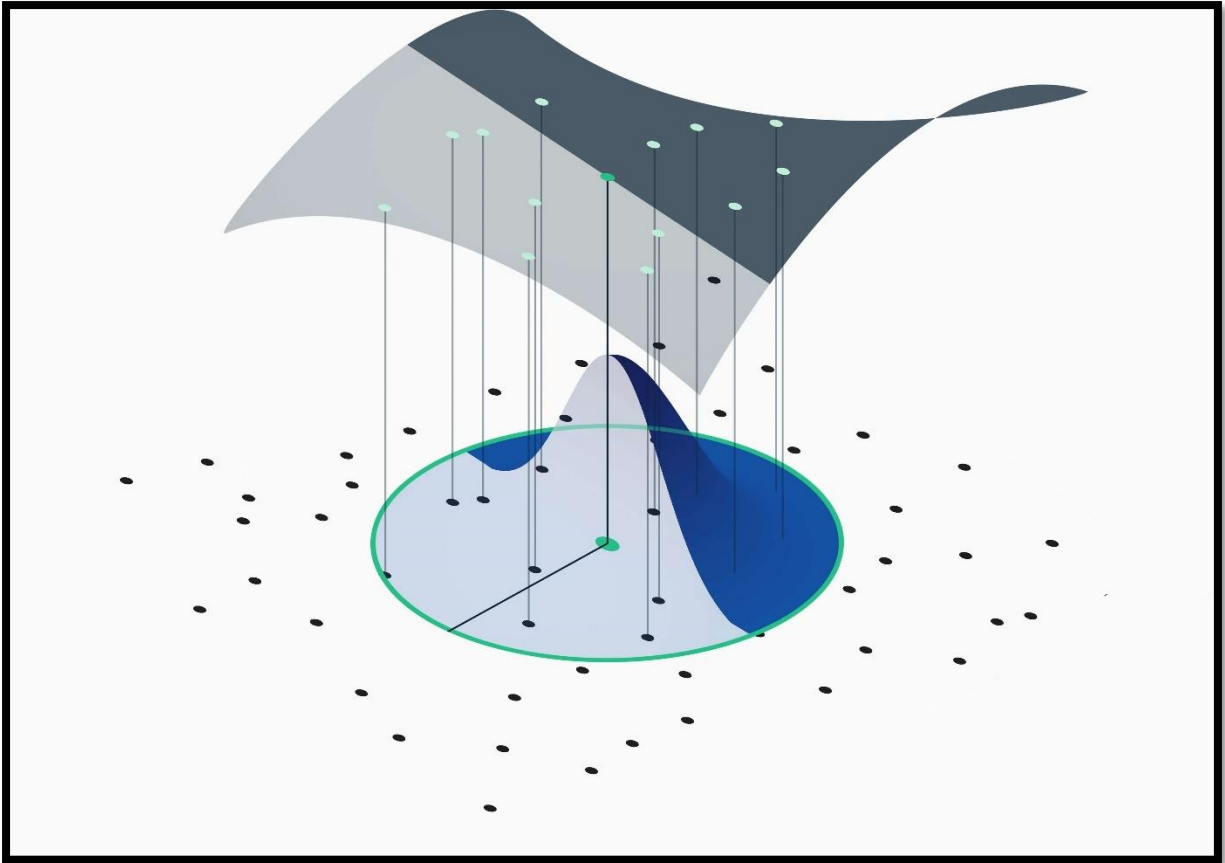


Figure 21. SPH Simulation (Tschirschnitz and Sabrowski, 2020)

SPH is advantageous with fluid influenced by deformation. Understanding pressure and velocity differentials are based on particle locations at set times, therefore, can handle moving boundary conditions with continuous calculations.

Conversely, SPH requires increased processing time and power, due to individual particle analysis of Kernel weight, thus, is only suited for complex simulations (Tschirschnitz and Sabrowski, 2020).

6.0. Task Five – Fluid Flow Experiment

An experiment can be completed, and quantities discovered can be compared to those derived in CFD.

6.1. Experiment Method

Boundary consideration will affect the chosen experimentation methods. Streckwall, Greitsch and Scharf (2013, pp.1-7) state scaling errors occur, with scale calculations having some margin of error with further limited boundary conditions which are further supported by Heinke, Hellwig-Rieck and Lübke (2019, p.5).

Therefore, a full-scale Cavitation Tunnel shown in figure 22 can be utilised to test hydrodynamic propeller performance, placed in the testing area shown in figure 22 at the top of the tunnel.

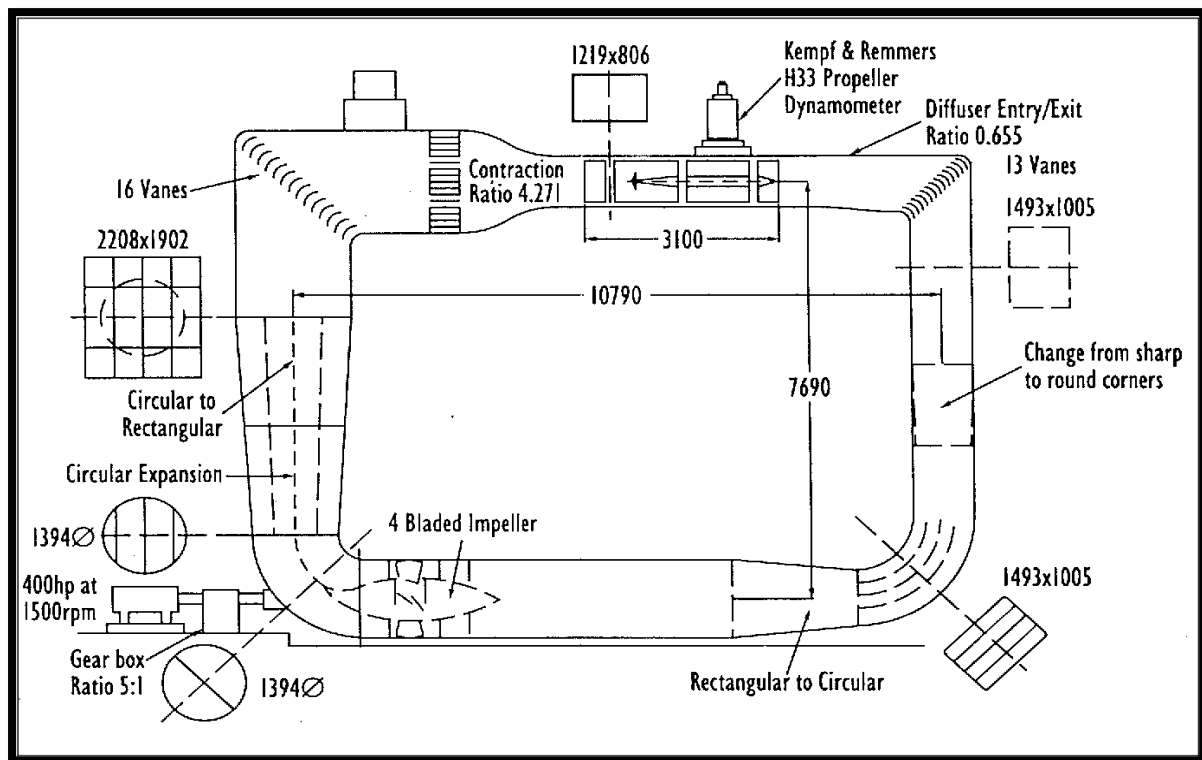


Figure 22. Cavitation Tunnel (Atlas, 2011)

A propeller attached to a shaft by the hub will rotate at typical tanker RPM by an external motor. This will drive the fluid around the cavitation tunnel, whilst simulating fluid flow through the propeller. For increased accuracy, simulating open waters, external motors will drive an impeller seen at the bottom of the cavitation tunnel in figure 22, producing this flow

type. The cavitation tunnel will have the same boundary conditions set in the CFD as table 9 shows. This ensures the results can be analysed effectively and compared (Aktas et al., 2022, pp.4-5).

Table 9. Boundary Conditions

Boundary	Condition
Inlet Velocity	Fixed and Constant
Propeller RPM	Fixed and Constant
Fluid Density	Set at Saltwater Density
Fluid Temperature	Fixed and Maintained to Open Water Temperature
Propeller Diameter	Fixed Size
Number of Blades	Fixed Number
Blade Pitch	Fixed Pitch
Material	Fixed Material (Fixed Friction Coefficient)

Once the boundary conditions are set, the measurement systems must be set, to obtain the quantities required for analysis. Body and fluid flow can be studied in two or three dimensions utilising Stereo Particle Image Velocimetry (S-PIV). Structures can be measured through deformations with Stereo Digital Image Correlation (S-DIC). Figure 23 shows the propeller in operation during cavitation testing compared to a CFD simulation. The fluid behaviour and quantity measurement instrumentation is shown in figure 24 (Cavitation Tunnel, 2022).

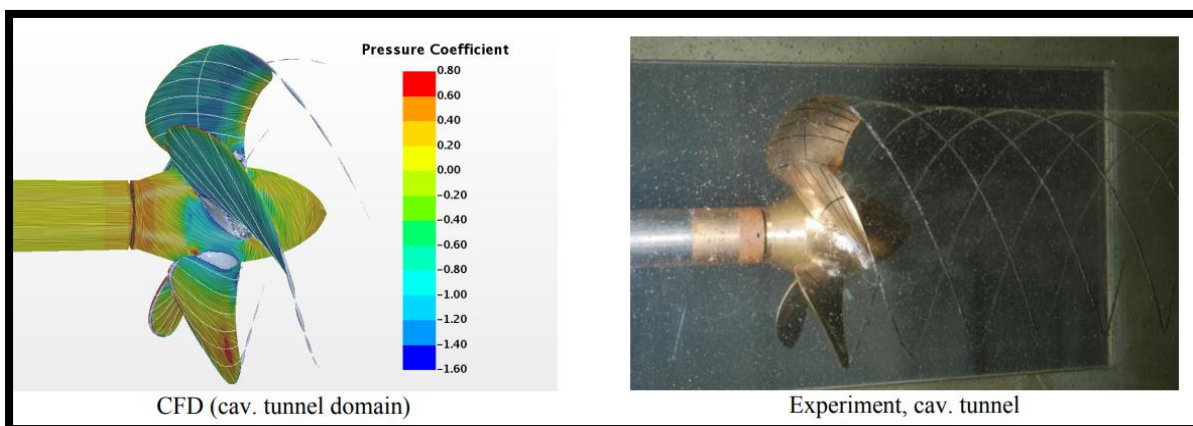


Figure 23. CFD vs Experiment (Krasilnikov (2022))

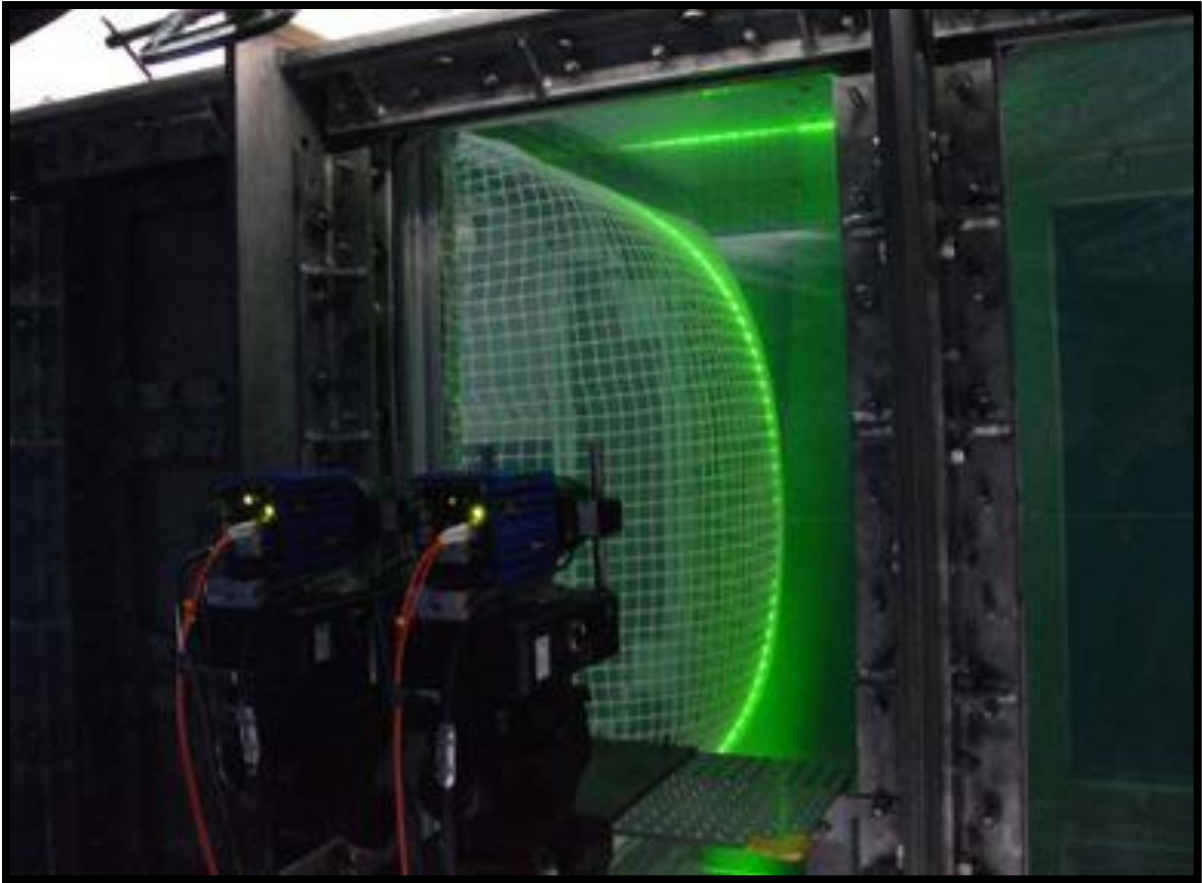


Figure 24. Experiment Testing Equipment (Cavitation Tunnel, 2022)

Tikkanen (2018) states cavitation is the formation of boiling vapour bubbles which may occur during the experiment, therefore, Krasilnikov (2022, pp.9-10) states this must be accounted for within the CFD with fine meshes to ensure accurate experimental comparison.

The International Towing Tank Conference (2017) set experimental standards, suggesting equipment calibration is essential, such as pressure gauges, thrust and torque dynamometer load response and other instrumentation calibration, thus, ensuring accurate readings.

Standards conformity ensures reliability, with boundary condition confidence, therefore, obtaining accurate fluid characteristic results (Aktas et al., 2022, p.6).

An effective way to understand high-level fluid characteristics and propeller performance is to utilise non-dimensional coefficients, such as:

$$K_T = \frac{T}{\rho n^2 D^4}$$

$$k_Q = \frac{Q}{\rho n^2 D^5}$$

$$\eta_0 = \frac{K_T J}{K_Q 2\pi}$$

$$J = \frac{V_a}{nD}$$

Table 10. Variable Descriptions

K_T	Thrust Coefficient
K_Q	Torque Coefficient
T	Propeller Thrust
Q	Propeller Torque
ρ	Fluid Density
D	Propeller Diameter
J	Advance Coefficient (Ratio of freestream fluid speed to propeller tip speed, therefore, it is the actual forward speed)
n	Propeller Revolutions Per Second
η_0	Propeller Efficiency
V_a	Freestream Fluid Velocity

Obtaining the coefficients allows one to analyse the CFD and experiment as a whole, understanding the effectiveness of the propeller and comparing that to the CFD on a high level before breaking down individual areas of propeller blade analysis. For example, obtaining propeller thrust, torque and efficiency, not only allows for CFD and experiment comparison but also allows for propeller design influence on the fluids at a high level. Then, low-level analysis can be completed from this data, finding high-pressure regions, fluid direction, boundary layer separation, velocities over various regions and so on.

Therefore, setting standards and implementing correct techniques is vital for understanding how fluid characteristics are influenced by propeller design and operation. For example, material impurities may affect friction coefficients, causing turbulent flow, which can only be determined if CFD and experimental boundary conditions are the same.

7.0. Conclusion

Understanding Fluid mechanics aid in propeller design. Reynolds Number allows one to understand fluid states, being laminar or turbulent which affects boundary layers. Reynolds Number and boundary layer manipulation ensure effective propeller operation.

Material selection also affects propeller operation. Carbon Fibre Reinforced Plastic unofficially meets regulatory standards, whilst exceeding property requirements, although further development and testing are required for commercial propeller implementation.

Design considerations can be simulated, thus, applying the fluid mechanic theories through many computational methods. These can be further compared to experiments, which are recommended to be full-scale to reduce inaccuracies.

Therefore, although propeller design can be complicated, foundational knowledge and understanding of the various techniques and methods one can utilise to analyse the design will allow one to produce a more efficient and reliable propeller. Thus, one could utilise this report to carry out experiments on various propeller designs and provide further development into Carbon Fibre Reinforced Plastic propellers, which may lead to a new innovative approach for a successful propeller.

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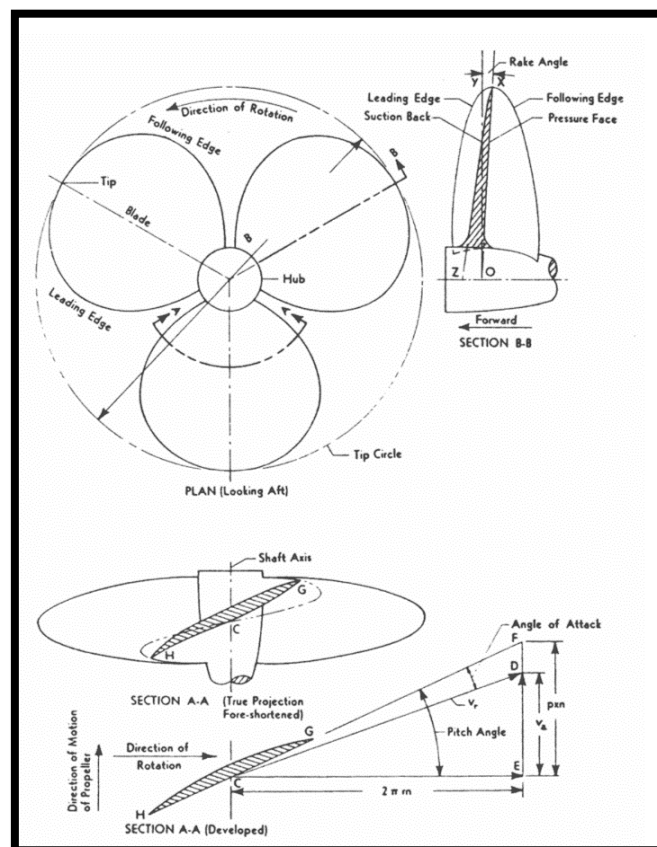
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Appendix One

Pitch indicates the distance the propeller would drive forward with each full rotation. For example, if the pitch was 500mm nominal, this would indicate the propeller would move the vessel forward 500mm for every cycle. However, slip does occur, meaning the nominal pitch and actual distance are not exact. That being said, the blades are twisted in order to guarantee a constant pitch along the blades from the root to the tip. The figure below shows the pitch on a propeller.

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Shows Propeller Pitch Geometry

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