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Designing a Kiteboard: Fluid flow assignment

STRUCTURAL & FLUID ANALYSIS (ACMA6010)

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1.0 Introduction

This report will discuss the fluid flow around a kitesurf board shown in operation in Figure 1. Figure 2 shows a kitesurf board's FE (Finite Element) model.



Figure 1 A Kitesurf board in use (University of Wales Trinity Saint David, 2024)

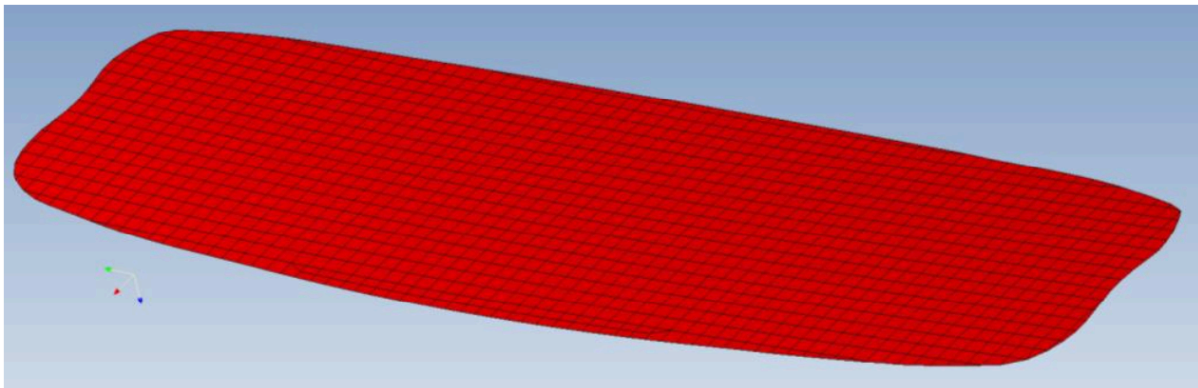


Figure 2 FE model of a kitesurf board (University of Wales Trinity Saint David, 2024)

Items such as Reynolds number, boundary flow, material choice, FE simulation and modelling techniques, prototyping and real-world experiments will all be discussed in this report.

Each section of this report will have a detailed analysis of the above fluid flow areas/concepts.

2.0 Reynolds number

Reynolds number (Re) is a dimensionless number, meaning it is a quantity with no units. Re is used in fluid flow mechanics to quantify the ratio of internal forces against the viscous forces within the fluid, relative to the fluid's velocity and distance travelled. The Re of the fluid in the situation can then determine if the fluid has laminar or turbulent flow. Re can be calculated by multiplying the fluid density, velocity, and the significant length of the object and then dividing this by the fluid's dynamic viscosity.

Reynolds number can be calculated using the two below formulas.

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

$$Re = \frac{u \cdot l}{V}$$

Where:

u = velocity (m/s)

l = significant length (m)

ρ = density (kg/m³)

μ = dynamic viscosity (kg/m.s)

V = kinematic viscosity (m²/s)

To calculate the Reynolds number for the kitesurf board, the fluid's velocity, the board's significant length, and the fluid's density and viscosity are required. The kitesurf board works by the operator standing on the surfboard component whilst holding onto a large kite that captures the wind higher up from the surfboard and, therefore, pulls the surfboard and operator along the water's surface.

To calculate Reynolds's number, some assumptions will need to be made to simplify the scenario to one that can be answered with hand calculations.

Firstly, the surfboard can be simplified to a flat plate rather than its actual geometry. Secondly, it can be assumed that the surfboard is stationary and the water below it travels at a set velocity. Lastly, as kite surfboards are used in seawater, a location must be selected so that the appropriate thermo property values are used within the

calculation; this report will assume the kitesurf board is being used in the Mediterranean Sea in July just off the Greek island of Rhodes.

According to the University Corporation of Atmospheric Research, the density of seawater at the sea surface is around 1.027 kg/m^3 (UCAR, 2000).

The kitesurf centre website (thekitesurfcentre.com) quotes the various speeds kitesurfing equipment can reach. They state that a surfboard variant can reach speeds of 38 mph, which is a top speed, and they also mention that they cruise around 15-20 mph. When calculating the Reynolds number, it is best to use the cruising speed as this is the condition the operator will most likely be subject to. Converting from a mile per hour to the scientific standard meters per second, we get a velocity value of $20 \text{ mph} = 8.9408 \text{ m/s}$; for the calculation, this will be rounded to 9 m/s .

The dynamic viscosity of seawater varies depending on salinity and the temperature of the water. From our third assumption, the salinity of the Mediterranean Sea at the chosen location is around 38 parts per thousand or 38 g/kg (Britannica, 2024). The surface temperature of the Mediterranean Sea in July at the chosen location is around 25 degrees Celsius (Sea Temperature.org, 2024). Using a datasheet produced by the Massachusetts Institute of Technology (MIT), the dynamic viscosity of the fluid can be set to $0.959 \times 10^{-3} \text{ kg/ms}$ (MIT, 2016).

Lastly, the significant length for the calculation is required. This is the length of the board. According to woodboard.com, a person weighing 65 – 80 Kg should use a board 135-138cm long (<https://woodboard.at/the-right-kiteboard-size-for-beginners-and-upcoming-riders/>). This can set the significant length to 138cm or 1.38m.

These values are inputted into the Reynolds number equation.

Values:

$$u = \text{velocity (m/s)} = 9 \text{ m/s}$$

$$l = \text{significant length (m)} = 1.38 \text{ m}$$

$$\rho = \text{density (kg/m}^3\text{)} = 1.027 \text{ kg/m}^3$$

$$\mu = \text{dynamic viscosity (kg/m.s)} = 0.959 \times 10^{-3} \text{ kg/ms}$$

$$Re = \frac{u \cdot l \cdot \rho}{\mu}$$
$$Re = \frac{9 \times 1.38 \times 1.027}{0.959 \times 10^{-3}}$$

$$Re = \frac{12.75534}{0.000959}$$

$$Re = 13,300.667$$

$$Re \approx 13,300$$

A fluid flowing along a flat plate with a Reynolds number of less than 50,000 is considered laminar. This means there is no separation of the fluid from the board and, therefore, little drag. Most of the force captured by the kite will go towards accelerating the user along the water's surface and not being lost to friction and drag within the contact of the seawater and surfboard.

3.0 Boundary flow

Boundary flow is a concept in fluid dynamics that describes the behaviour of fluids near a solid body. The fluid layer in direct contact with the solid body has zero velocity relative to the boundary surface due to a phenomenon known as the non-slip condition. As the distance from the surface increases, the velocity of the fluid layer increases towards the fluid's free stream velocity, creating a velocity profile for the fluid, as seen in Figure 3. Any flow less than 99% of the free stream velocity is considered within the boundary flow. The velocity profile for typical laminar flow is curved, as shown in Figure 3, due to the frictional forces within the fluid and the non-slip condition. The fluid in the layer touching the non-moving fluid shears across the touching layer, resulting in frictional losses and, therefore, reducing the velocity of that layer. This is repeated with the subsequent layers until the fluid moves at the free stream velocity.

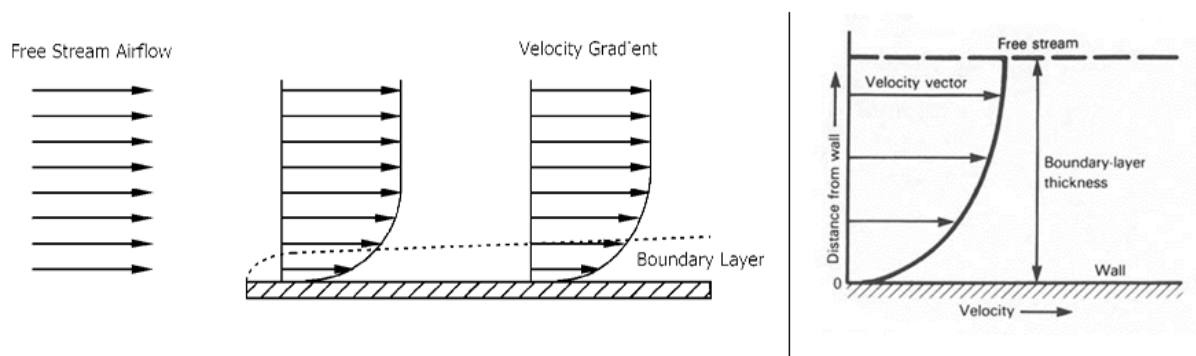


Figure 3 Boundary layer/ velocity profile (engr, 2024)

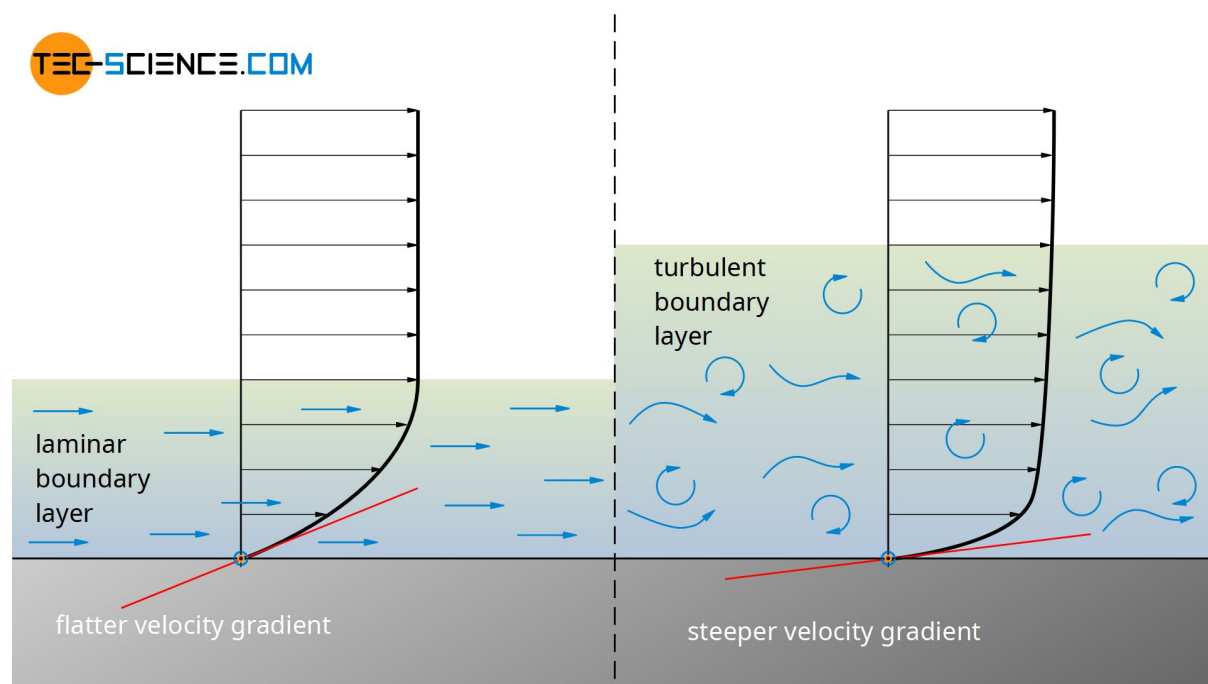


Figure 4 Velocity profile in a laminar and turbulent boundary layer (Tec-Science, 2020)

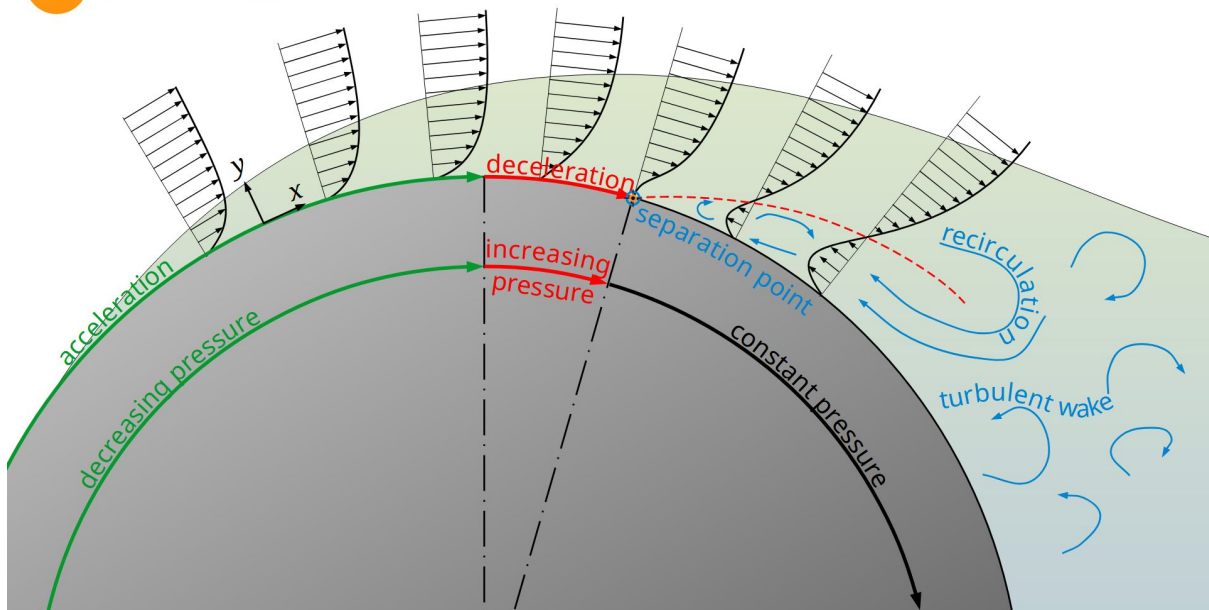


Figure 5 Velocity distribution along a flow around a cylinder (flow separation) (Tec-Science, 2020)

The board seen in Figure 2 has soft leading edges around it, as the user may make quick adjustments in direction due to changes in wind and waves. The soft curves on the board's edge allow the seawater to easily run off the board and not get caught at sharp angles. This all relates back to the user turning with less resistance from the board and water.

4.0 Material Choice

It has been suggested that the board is made from carbon fibre-reinforced plastic. This composite material would consist of layers of plastic with carbon fibre rods laid in between the plastic layers. This is done to give the material better tensile strength in certain directions. The default plastic will have a level of strength, but the carbon fibres will give the composite a higher level of tensile strength without the need to be fully made from carbon fibre. This is similar to how reinforced concrete enhances standard concrete.

The board is made from a material like this is generally good as it gives the board strength in all directions rather than just in one axis. As the user will be continually adjusting the board's direction and, therefore, the orientation of the stress concentrations, the board needs to be made from a material that can withstand this. Carbon fibre-reinforced plastic is an economical solution for this.

Historically surfboards and other water-based boards have been made from high-strength foam that is then wrapped in a laminating plastic; looking even further back surfboards have been made from various natural sources such as wood.

Due to the irregular shape of the source material, wooden boards would be extremely difficult to manufacture in large quantities and extremely expensive; each board would need to be hand-made, which would take time and money.

Foam boards are still used in the industry, but generally at the entry level. This is due to the strength of the boards. As users become more proficient, they may wish to try harder skills or go faster. All of this puts more stress on the board, and the foam design can tend to fail due to these forces exerted on the board. For these reasons, professionals will tend to use modern boards made from composite materials.

5.0 Modelling techniques

Computational fluid dynamic (CFD) software could simulate the board and calculate the forces exerted onto it. This information can then be inputted into a finite element analysis (FEA) model to see how the chosen material and geometry would withstand these forces and where the stresses within the material would be.

The CFD model would need to be set with a weight force representing the user acting evenly downwards on the board. There would need to be a fluid boundary where the board meets the seawater. CFD software works by splitting the fluid area into small individual elements, known as meshing the model. Once the model has been meshed, start and end conditions will be set for the simulation. This could be a steady state volume or mass flow rate; the software will then solve the Navier-Stokes equations for each element within the mesh and the elements surrounding them. The software will run hundreds or even thousands of iterations for each element until the program has calculated the correct values to reach the start and end goals, known as the values converging. (<https://www.grc.nasa.gov/www/k-12/airplane/nseqs.html>)

The Navier-Stokes equations seen in Figure 6 consist of four equations. These equations describe how a moving fluid's pressure, velocity, density, and temperature are related. G.G. Stokes in England and M. Navier in France derived the equations independently in the 1800s. The Navier-Stokes equations are an extension of the Euler equations from the mid-1700s, but unlike the Euler Equations, the Navier-Stokes equation includes the effects of viscosity on the flow. (NASA, 2021)

The continuity equation describes the conservation of mass with a time-dependent variable. There are three time-dependent conservation of momentum equations, one for each direction (x, y, and z). Lastly, there is a time-dependent conservation of energy equation. These equations consist of four independent variables: the x, y and z spatial coordinates within the domain and the time variable. There are six dependent variables within the four equations: pressure, density, temperature and three velocity vector variables, one for each direction.



Navier-Stokes Equations

3 - dimensional - unsteady

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Coordinates: (x,y,z)	Time : t	Pressure: p	Heat Flux: q
Velocity Components: (u,v,w)	Density: ρ	Stress: τ	Reynolds Number: Re
	Total Energy: Et		Prandtl Number: Pr

Continuity:
$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X - Momentum:
$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right]$$

Y - Momentum:
$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right]$$

Z - Momentum:
$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right]$$

Energy:
$$\begin{aligned} \frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = & -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r} \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \\ & + \frac{1}{Re_r} \left[\frac{\partial}{\partial x}(u \tau_{xx} + v \tau_{xy} + w \tau_{xz}) + \frac{\partial}{\partial y}(u \tau_{xy} + v \tau_{yy} + w \tau_{yz}) + \frac{\partial}{\partial z}(u \tau_{xz} + v \tau_{yz} + w \tau_{zz}) \right] \end{aligned}$$

Figure 6 Navier-Stokes Equations - 3 dimensional - unsteady (NASA, 2021)

The calculated pressures due to the flow around the board found using CFD could then be inputted into an FEA program to calculate the internal stresses within the board and if it will fail or if there are any weak areas in the design.

FEA simulations calculate the internal stresses and displacement for a given situation on a given geometry, such as an external load force on a beam. The software applies various equations, such as the equilibrium equations, constitutive equations, and strain-displacement equations.

Both CFD and FEA are excellent tools for engineers to estimate how a component will react to a known situation, but engineers will still use real-world testing to prove the component is real-world worthy; these tests can be material sample tests such as simple tensile strength test or more complex testing for the whole components such as a BAM oxygen test will be undertaken on oxygen gaskets and hoses that will be operating at high pressures and temperatures, this test exposes the element to oxygen at extremely high velocity, mass flow and pressure to see if the component can withstand the environment it may be subject to in the real world. CFD and FEA struggle to calculate how the materials and oxygen will react at these high pressures and speeds; this is mainly due to the density of the medium not being constant at

these speeds and pressures, which makes the equations much more complicated. Therefore, a real-world test is the best way to know if a component such as this will fail in the real world.

6.0 Prototyping and Testing

There are various ways to prototype and test this kitesurf board. A full-scale foam model can be produced quickly and relatively inexpensively. This model can be used to simulate the flow around the board using a water bath with a coloured die to see the turbulence and drag tail created by the board. The foam can also be wrapped in a thin layer of carbon fibre-reinforced plastic on the underside, so the boundary layer is comparable to the final production component.

Scaling the model down can also be done, but then the engineers must calculate the accurate scale results as the separation distance will not scale down linearly. To simulate the forces exerted on the prototype, a simple hydraulic/ pneumatic piston can replicate the user's weight force, and a pump can create the correct flow rate within the water to replicate the board moving at the appropriate velocity.

To capture the data from the testing, the engineers may use a coloured die to visually see the flow around the board, along with g-force sensors and accelerometers that will record the slightest movement of the board due to the flow around it. The accelerometers can then be inputted into the appropriate software to playback the spatial points chosen on the board on a computer.

High-speed cameras can capture the coloured die within the water as the flow may change too quickly for the human eye to observe and report back accurately. A mixture of the devices mentioned above should allow the engineers to understand the forces acting upon and around the board. The experiment can also be adjusted to modify the user's weight, the board's velocity and the angle of attack on the water to simulate turning on the seawater surface.

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