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Structural and fluid analysis

Designing a wind turbine blade:
Aerodynamic design

Mechanical & Manufacturing Engineering
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Introduction

This assignment focuses on the fluid flow around a wind turbine blade and looks at why the angle of the blade changes along its length to maintain efficiency and not stall. It discusses how important the Reynolds number is and what influences it has on the flow around the blade. The boundary flow around the aerofoil, relating to separation and turbulence is also discussed to understand what happens when the fluid passes over a surface. Furthermore, using a given scenario and reasonable assumptions, the Reynolds number for the blade is estimated and evaluated to give a better understanding of the fluid flow. In addition to this trigonometry is used to estimate the angles at play such as the flow angle, pitch angle and angle of attack and explain if/why they change.

Task 1 & 2 – Discuss the Reynolds number and the boundary flow around the air foil.

$$\text{Reynolds Number (Re)} = \frac{\text{Density } (\rho) \times \text{Velocity } (v) \times \text{Significant length } (L)}{\text{Viscosity } (\mu)}$$

The Reynolds number is a unitless number, used to describe whether the fluid is laminar, turbulent or in transient flow. When the Reynolds number is less than 2300 the flow is described as laminar. Between 2300-4000 is known as transient flow and over 4000 is known as turbulent flow. (Soft Schools, 2020) Over a surface, a Reynolds number greater than 200000 is assumed to have a turbulent boundary flow (See Figure 1).

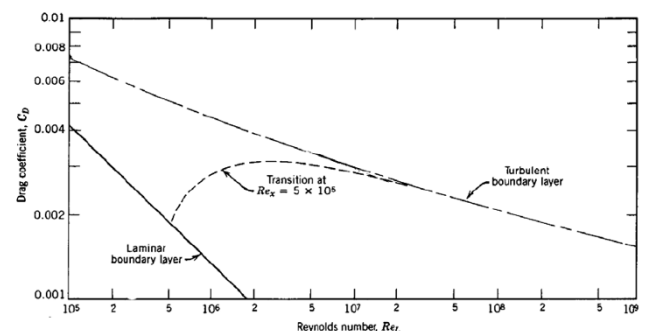


Figure 1- Graph showing Reynolds number against Drag Coefficient over a flat plate. (Ujile, 2020)

The Reynolds number shows the relationship between the size of the viscosity and the size of the forces. A larger viscosity would result in a smaller Reynolds number. This suggests that at larger Reynolds number would have a smaller viscosity and therefore less friction.

Viscosity - the state of being thick, sticky, and semi-fluid in consistency, due to internal friction. (Oxford Languages, 2020) The definition of viscosity implies internal layers. These layers can be either laminar or turbulent. Layers are represented by trajectories (streamlines) See Figure 2. Laminar flow is when the trajectories run parallel. Turbulent

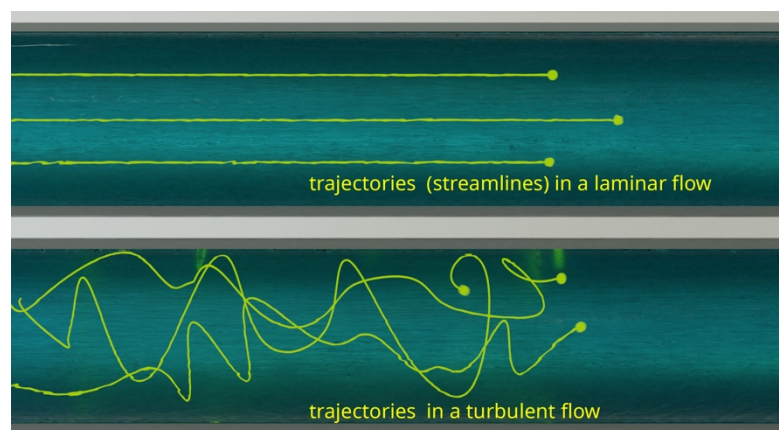


Figure 2- Figure to show laminar and turbulent flow (Tec Science, 2020)

flow is unorganised. (Tec Science, 2020)

An estimation of the Reynolds number can be made with some reasonable assumptions. The density and viscosity of air changes with temperature and height. The conditions assumed to obtain the results is air at 10°C at sea level. The average windspeed in the UK is 8.2 knots (4.22m/s) (Tiseo, 2020) for analysis a windspeed of 5m/s will be used. The wind velocity at sea could be higher than this, which would increase the Reynolds number, but 5m/s will still provide an adequate estimation.

Density of Air at 10°C: 1.246kg/m³

(Engineers edge, 2020)

Viscosity of Air at 10°C: 1.778x10⁻⁵ kg/m-s

(Engineers edge, 2020)

Velocity of wind: 5 m/s

Significant length: 665mm

$$Re = \frac{1.246 \times 5 \times 0.665}{1.778 \times 10^{-5}}$$

Re = 233011.8

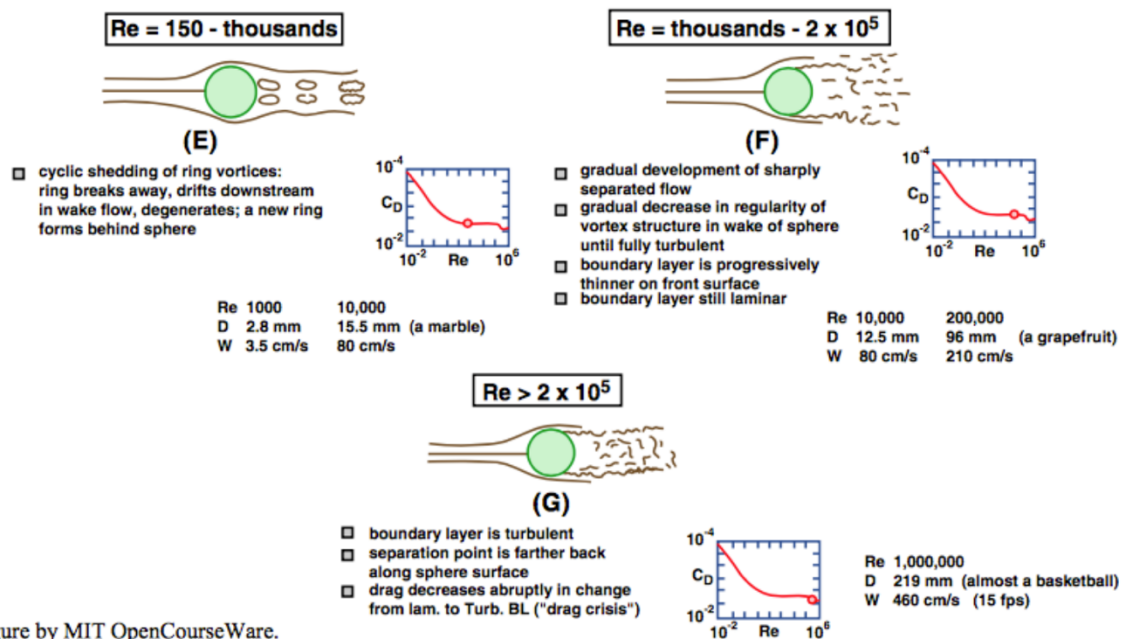


Figure by MIT OpenCourseWare.

Figure 3 - Representation of flow at different Reynolds numbers (MIT OpenCourseWare, 2020)

The Reynolds number is estimated to be over 200,000. Figure 3 shows how fluid flows around a sphere at different Reynolds numbers. It shows that over 200000 the boundary layer becomes turbulent which pushes the layer separation further back. If the boundary flow is turbulent the form drag is reduced. Form drag is the drag associated with objects effect on the airflow. It occurs when the layers separate and produce wake. (Skybrary, 2017)

“Turbulence in the boundary layer increases the transport of momentum from the free stream and therefore delays separation. The separation point moves towards the back of the sphere and the size of the wake reduces.”
(Juniper, 2020)

According to Juniper, the turbulent boundary flow on the blade delays the layer separation which results in less form drag. Less drag means more lift, making the blade more efficient.

Figure 4 shows pressure distribution with and without turbulence. On the righthand side we can see that the flow separation is delayed in the turbulent flow, which aids lift. This supports the suggestion that turbulent boundary flow delays separation producing more lift, due to a reduction in drag.

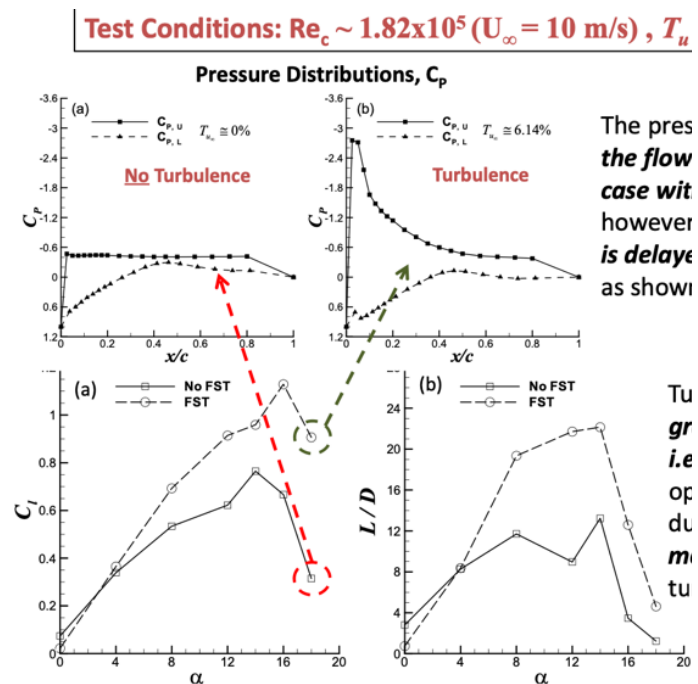


Figure 4- Figure to show experiment results, graphs showing pressure distribution and coefficient of lift against attack angle. (Luciano Castillo, 2020).

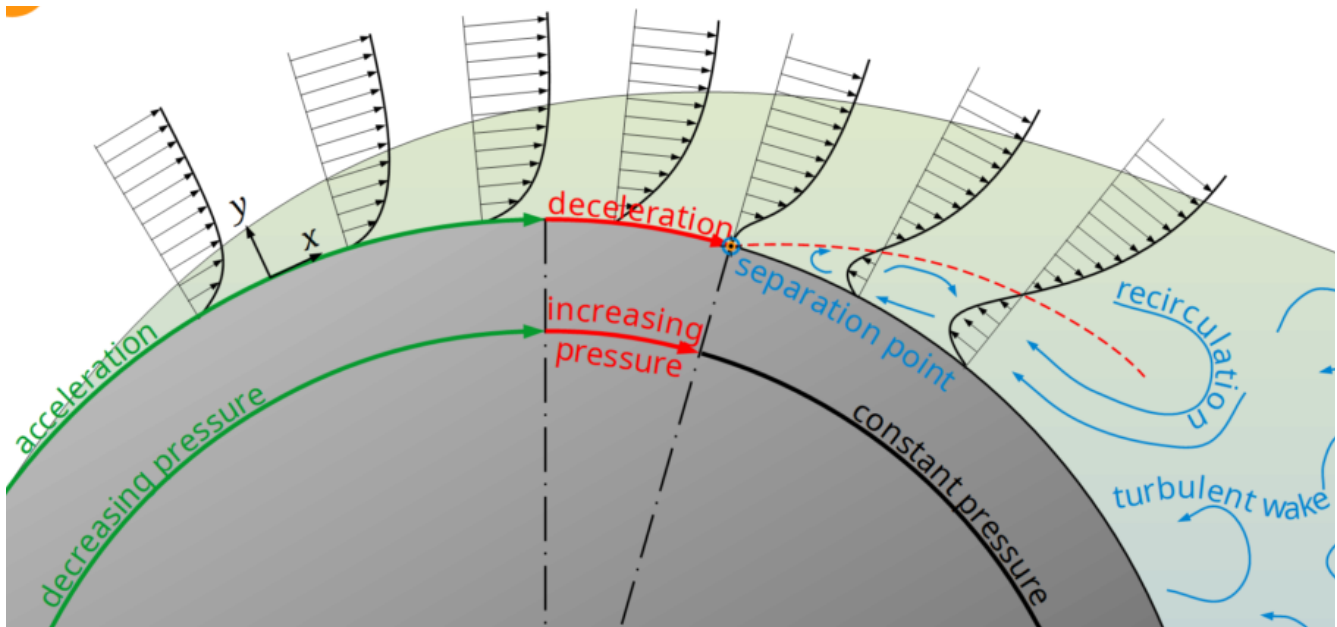


Figure 5 - Velocity distribution along a flow around a cylinder (flow separation (Tec- Science, 2020))

Flow separation occurs when the velocity gradient in the y direction becomes 0 and the velocity profile flattens out (See figure 5). According to Newton's law of fluid friction, Force $\sim$ Area * (Velocity difference/Fluid layer thickness)

$$F \sim A \times \frac{\Delta v}{\Delta y}$$

Force/ Area = Shear stress:

$$\frac{F}{A} = \tau$$

Velocity difference/ Fluid layer thickness = Shear rate (Velocity gradient):

$$\frac{\Delta v}{\Delta y} = \dot{\gamma}$$

Therefore:

$$\frac{F}{A} = \frac{\Delta v}{\Delta y} \therefore \tau = \dot{\gamma}$$

(Tec- Science, 2020)

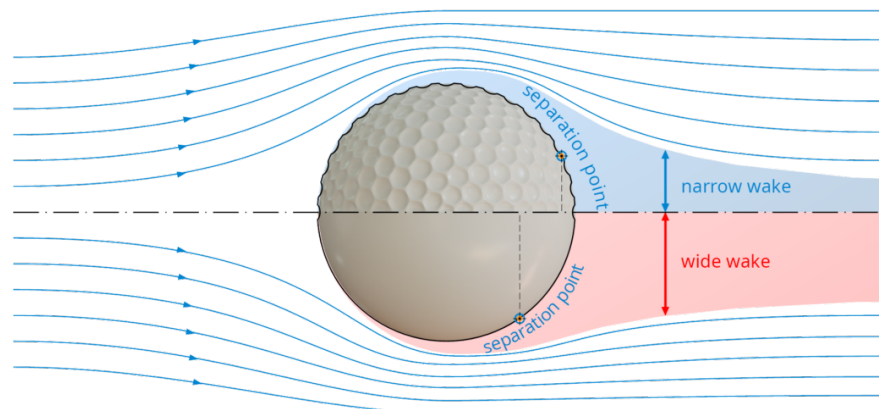
This means that when the gradient in the y direction is 0 the shear stress is 0 and the fluid no longer adheres to the surface of the body.

(Hyperphysics, 2020) The velocity in the y direction increases faster in turbulent flow than in laminar flow. This suggests higher velocity in the boundary layer as fluids flow slower when close to the surface, due to viscosity. Bernoulli's equation states that change in kinetic energy is linked to a change in static pressure: $P_1 + \frac{1}{2}\rho v_1^2 + \rho gh_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho gh_2$

When separation occurs pressure drops and creates more form drag. The higher velocity in a turbulent boundary layer results in increased transport of momentum, which allows the fluid to follow the profile of the object for longer, narrowing the wake produced and reducing the form drag. (Tec- Science, 2020) "The resulting higher kinetic energy of the boundary layer can counteract the adverse pressure gradient more, so to speak." (Tec- Science, 2020)

This reduction in drag improves the efficiency of the wind turbine, meaning more energy can be harvested from the wind.

An example of how turbulent flow can be beneficial is seen on golf balls. Dimples are added to create turbulent flow, which in turn pushes back the point of separation and reduces wake, therefore reducing fluid flow loss / drag.



A laminar boundary flow reduces the amount of fluid loss. But if layer

Figure 6 - An example of how turbulent flow can effect separation point. (Tec- Science, 2020)

separation is expected to occur a turbulent boundary layer is favourable to delay separation. (Tec- Science, 2020)

In a turbulent boundary flow, the skin friction is reduced, but the drag that occurs from the turbulence and backflow of air is greatly increased. This is why it is desirable to have enough velocity in the turbulent boundary flow to carry the turbulence along the profile of the object and away from it. (Aerospace engineering, 2016)

Task 3 - How the flow angle changes along the length

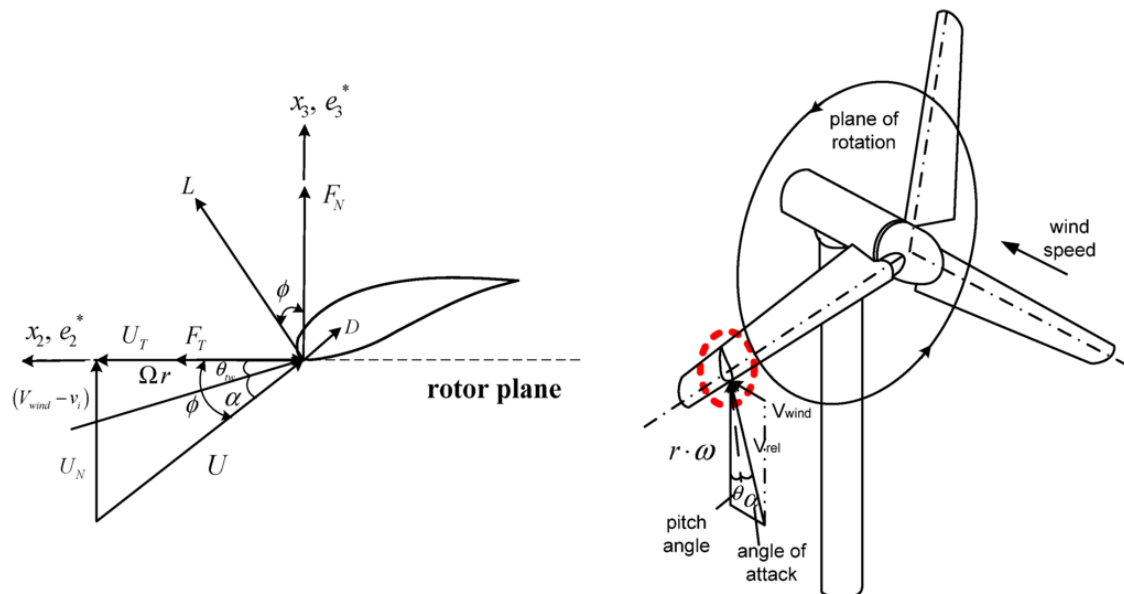


Figure 7- Diagram showing Vectors and angles around wind turbine blade (Min-Soo Jeong, 2013)

The diagram in Figure 1 represents a propeller.

U_N – Windspeed (15m/s)

U_T – Tangential velocity

U – Apparent windspeed (resultant force)

α - Angle of attack

ϕ - Apparent angle

θ - Pitch angle

Angle $U_N - U$ – Flow angle

The wind speed is given as 15 m/s. The Tangential velocity changes along the blade. It can be calculated at points along the length of the blade, by using the rotational speed, which is given as 1 rotation per second. These can be used to work out the resultant force and the internal angles.

Distance Along blade (m)	Tangential Velocity (m/s)
1	6.28
2	12.57
3	18.85
4	25.13
5	31.42
6	37.70
7	43.98
8	50.27
9	56.55
10	62.83

Table 1- Table to show Tangential velocity (m/s) along length of blade.

Tangential velocity can be calculated by working out the distance the point travels, i.e. the circumference. Circumference is equal to $\pi \times \text{Diameter}$. As we know the blade completes 1 full rotation a second, the circumference is equal to the velocity in m/s.

The Tangential velocity will not be exact due to the fact the distance between the base of the blade and the centre of rotation are not known, but can give us a good representation of how the angles should change along the length of the blade.

We can use the Windspeed (U_N) and the Tangential Velocity (U_T) to work out the resultant vector (U) (Apparent windspeed).

Table 2- Table showing resultant vector values along the length of the blade.

Dist' Along blade (m)	Tangential Velocity (m/s)	Resultant vector (m/s)
1	6.28	16.26
2	12.57	19.57
3	18.85	24.09
4	25.13	29.27
5	31.42	34.81
6	37.70	40.57
7	43.98	46.47
8	50.27	52.46
9	56.55	58.50
10	62.83	64.60
Wind Speed (m/s): 15		

The inner angles of the vector triangle can be worked out using Pythagoras theorem (See figure 9). The apparent angle ϕ is equal to $\tan^{-1} (U_N / U_T)$. The Flow angle is given by $\tan^{-1} (U_T / U_N)$

Table 3 shows that the flow angle increases as it gets further towards the tip of the blade.

Dist' Along blade (m)	Rotational Velocity (m/s)	Resultant vector (m/s)	Apparent Angle (°)	Flow Angle (°)
1	6.28	16.26	67.27	22.73
2	12.57	19.57	50.05	39.95
3	18.85	24.09	38.51	51.49
4	25.13	29.27	30.83	59.17
5	31.42	34.81	25.52	64.48
6	37.70	40.57	21.70	68.30
7	43.98	46.47	18.83	71.17
8	50.27	52.46	16.62	73.38
9	56.55	58.50	14.86	75.14
10	62.83	64.60	13.43	76.57
Wind Speed (m/s): 15				Angle of Attack (°): 11

Table 3- Table to show Apparent angle and Flow angle along the length of the blade.

The flow angle, (The green angle in figure 8) is the angle in which the windspeed and the resultant vector are linked at a given tangential velocity. As the Tangential force increases the flow angle increases.

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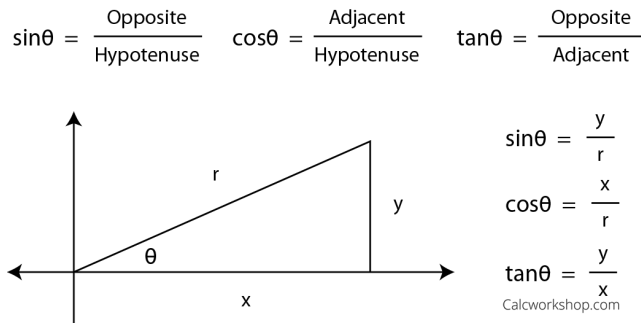


Figure 9 – Pythagoras theorem (Calc Workshop, 2020)

This can be proved by Pythagoras theorem:

$$\text{Flow Angle} = \tan^{-1}\left(\frac{\text{Tangential Velocity}}{\text{Windspeed}}\right)$$

As the tangential velocity increasing along the length of the blade, the flow angle increases. This means in order to utilise the flow angle the Apparent angle ($\phi = \theta + \alpha$) must decrease.

Task 4 – Show how the pitch of the blade must change along the length so that the blade does not stall.

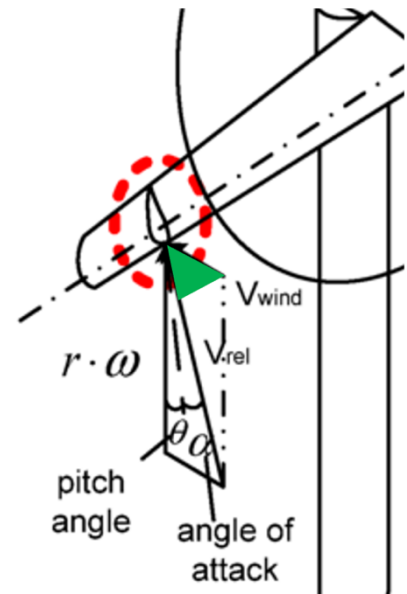


Figure 8 - Diagram showing Vectors and angles around wind turbine blade (Min-Soo Jeong, 2013)

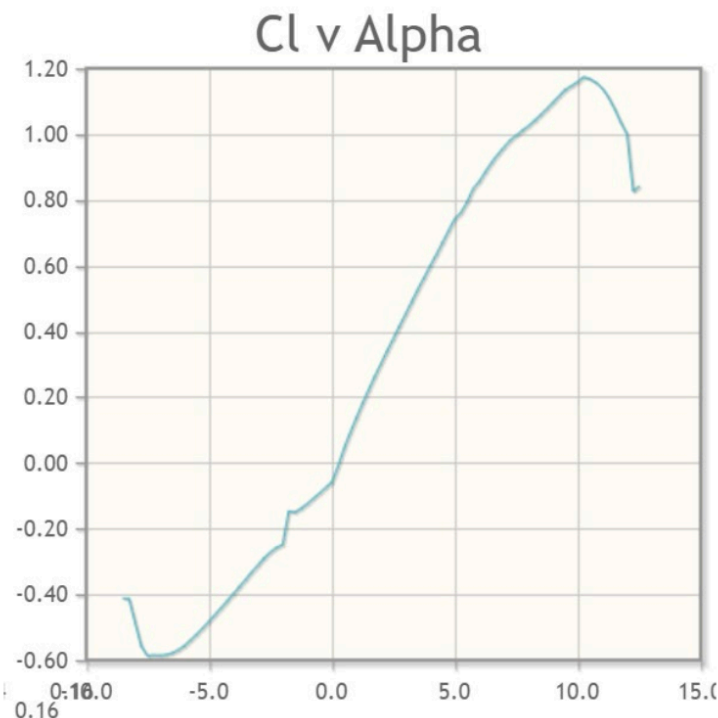


Figure 10 - Graph to show Coefficient of lift v Angle of Attack for the aerofoil used. (From Brief)

Figure 10 shows the coefficient of lift against the angle of attack for the aerofoil used. From around 2- 10° the coefficient of lift increases. The optimum angle of attack for the highest coefficient of lift is around 11°. Once steeper than 11° the coefficient of lift suddenly drops. This sudden drop in lift is known as a stall. For the turbine to perform at the optimum level, the angle of attach should be between 2- 11°, but as close to 11° as possible, without exceeding it. To keep the angle of attack at its optimum along the length of the blade, The pitch angle must change.

As we know the apparent angle, we can use this target for the angle of attack to work out the pitch angle.

$$\text{Apparent angle } (\phi) - \text{Angle of attack } (\alpha) = \text{Pitch angle } (\theta)$$

Dist' Along blade (m)	Apparent Angle (°)	Flow Angle (°)	Pitch Angle θ (°)
1	67.27	22.73	56.27
2	50.05	39.95	39.05
3	38.51	51.49	27.51
4	30.83	59.17	19.83
5	25.52	64.48	14.52
6	21.70	68.30	10.70
7	18.83	71.17	7.83
8	16.62	73.38	5.62
9	14.86	75.14	3.86
10	13.43	76.57	2.43
Wind Speed (m/s): 15		Angle of Attack (°):11	

Table 4- Table to show how pitch angles change along the length of the blade.

Wind turbines are often built tall as the air is viscous and sticks to the ground. Further away from the ground the air moves faster. It is assumed the wind will be travelling horizontal to the ground, at 90° to the direction of rotation. In order to keep the angle of attack at 11° and not exceed 11°, which would result in a stall due to a sudden drop in lift (Seen in figure 10), the pitch angle must change to compensate the change in tangential velocity. Table 4 shows that the pitch angle should decrease as it gets the further towards the tip of the blade. We can see a representation of how the pitch angle should change along the length of the blade in Figure 11. The closer towards the tip, the slower the angle decreases.

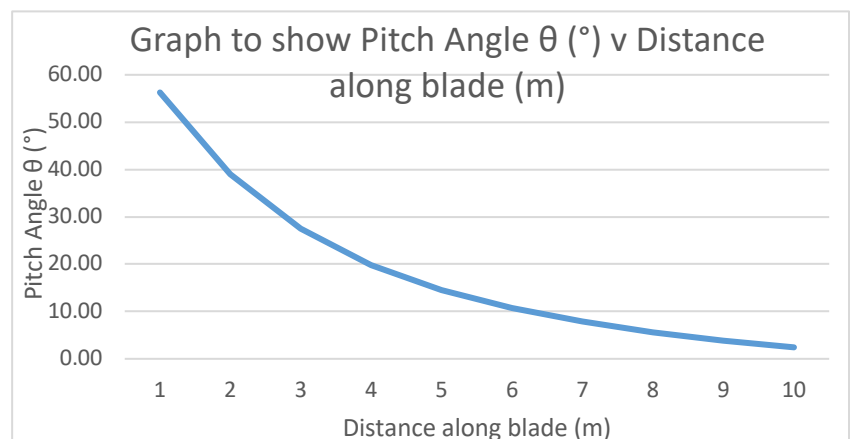


Figure 11- Graph to show Pitch Angle, along the blade length.

Keeping the blade at the correct pitch angle, with an angle of attack that generates a high coefficient of lift improves the effectiveness of the blade. The apparent wind speed, which with the tangential velocity along the blade, changes, the angle along the length of the blade, must change too. This allows the blade to capture as much wind energy as possible and generate lift, which is then used to generate power. The law of conservation of energy states that energy in is equal to energy out. (BBC Bitesize, 2020) Therefore the more wind energy captured the more power that can be generated.

Conclusion

To conclude, a laminar boundary flow is ideal, but if layer separation is inevitable, a turbulent boundary flow should be aimed for. This is due to an increase in velocity of the boundary flow, moving the point of separation back, reducing the form drag. With an estimated Reynolds number of over 200,000, even with relatively slow wind speed assumed, it is safe to assume a turbulent boundary layer is desirable.

Due to a change in tangential speed along the length of the blade, increasing as you get closer to the tip, there will be an increase in the flow angle. This is why the blade must twist. The coefficient of lift produced at different angles of attack defines the pitch angle that is needed

to ensure the optimum the efficiency of the blade. Overall the pitch of a wind turbine blade should follow the rate of change shown in figure 11 and decrease proportionally to the flow angle. This will keep the blade at its optimum and prevent it from stalling. An example of the change in angle along the blade can be seen in figure 12. The pitch angle decreases towards the tip of the blade, which supports the estimations made and shown in the Figure 11. It is important to ensure the angle of attack stays between 2° and 11° to prevent stall.



Figure 12 - Wind turbine example. (Alternative Energy Tutorials, 2020)

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Appendix

Dist' Along blade (m)	Rotational Velocity (m/s)	Resultant vector (m/s)	Apparent Angle (°)	Flow Angle (°)	Pitch Angle θ (°)
1	$= (A2^2) * \pi()$	$= \text{SQRT}((15^2) + (B2^2))$	$= \text{DEGREES}(\text{ATAN}(15/B2))$	$= \text{DEGREES}(\text{ATAN}(B2/15))$	=D2 -11
2	$= (A3^2) * \pi()$	$= \text{SQRT}((15^2) + (B3^2))$	$= \text{DEGREES}(\text{ATAN}(15/B3))$	$= \text{DEGREES}(\text{ATAN}(B3/15))$	=D3 -11
3	$= (A4^2) * \pi()$	$= \text{SQRT}((15^2) + (B4^2))$	$= \text{DEGREES}(\text{ATAN}(15/B4))$	$= \text{DEGREES}(\text{ATAN}(B4/15))$	=D4 -11
4	$= (A5^2) * \pi()$	$= \text{SQRT}((15^2) + (B5^2))$	$= \text{DEGREES}(\text{ATAN}(15/B5))$	$= \text{DEGREES}(\text{ATAN}(B5/15))$	=D5 -11
5	$= (A6^2) * \pi()$	$= \text{SQRT}((15^2) + (B6^2))$	$= \text{DEGREES}(\text{ATAN}(15/B6))$	$= \text{DEGREES}(\text{ATAN}(B6/15))$	=D6 -11
6	$= (A7^2) * \pi()$	$= \text{SQRT}((15^2) + (B7^2))$	$= \text{DEGREES}(\text{ATAN}(15/B7))$	$= \text{DEGREES}(\text{ATAN}(B7/15))$	=D7 -11
7	$= (A8^2) * \pi()$	$= \text{SQRT}((15^2) + (B8^2))$	$= \text{DEGREES}(\text{ATAN}(15/B8))$	$= \text{DEGREES}(\text{ATAN}(B8/15))$	=D8 -11
8	$= (A9^2) * \pi()$	$= \text{SQRT}((15^2) + (B9^2))$	$= \text{DEGREES}(\text{ATAN}(15/B9))$	$= \text{DEGREES}(\text{ATAN}(B9/15))$	=D9 -11
9	$= (A10^2) * \pi()$	$= \text{SQRT}((15^2) + (B10^2))$	$= \text{DEGREES}(\text{ATAN}(15/B10))$	$= \text{DEGREES}(\text{ATAN}(B10/15))$	=D10 -11
10	$= (A11^2) * \pi()$	$= \text{SQRT}((15^2) + (B11^2))$	$= \text{DEGREES}(\text{ATAN}(15/B11))$	$= \text{DEGREES}(\text{ATAN}(B11/15))$	=D11 -11
Wind Speed (m/s):				Angle of Attack (°):	
15				11	