COMPUTATIONAL AND EXPERIMENTAL STUDY ON HORIZONTAL-AXIS WIND TURBINE SLOTTED BLADE DESIGN

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Declaration

It is declared that the content of the thesis report titled "Computational and Experimental Study on Horizontal-Axis Wind Turbine Slotted Blade" has been prepared by me, Ling Siok Mei under guidance of Ir. Dr. Chan Keng Wai. It is further declared that this is my original work, as part of the requirement for the course titled EMD452 Final Year Project for Mechanical Engineering Degree at the School of Mechanical Engineering, Universiti Sains Malaysia.

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Signature

Name: Ling Siok Mei

Date:

Acknowledgement

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List of Abbreviations

P	Power extracted from wind
ρ	Air density
A	Swept area
v	Air velocity
L	Lift Force
D	Drag Force
C_L	Lift coefficient
C_D	Drag coefficient
C_{PD}	Design power coefficient of the rotor
P_D	Power expected at the design point
R	Rotor radius
E_a	Energy required for a specific application
η_d	Drive train efficiency
η_g	Generator efficiency
v_D	Design wind velocity
η_s	Overall system efficiency,
v_M	Daily mean wind velocity over a period
T	Number of hours in that period
λ_D	Design tip speed ratio
β	Blade setting angle.
C	Chord length
α	angle of attack
C_f	Flap chord ratio

C_α Lip position

δ_f Angle of slotted flap

toe Tonnes of oil equivalent

NACA National Advisory Committee for Aeronautics

Abstrak (BM)

Pada zaman moden ini, pertumbuhan teknologi tenaga angin di seluruh dunia semakin pesat. Perkembangan ini telah menunjukkan peranan tenaga angin sebagai sumber tenaga yang boleh diperbaharui ini memainkan peranan yang penting dalam komuniti kita. Pengoptimuman taknologi turbin angina adalah aspek yang penting dalam mengurangkan kos serta meningkatkan produktiviti tenaga angina. Mengoptimumkan reka bentuk topologi bilah turbin angin telah dijangka dapat mengatasi masalah kelajuan angin yang agak rendah di Malaysia bagi memenuhi keperluan loji kuasa angin yang berskala besar. Penyelidikan topik ini termasuklah mereka bilah berslot bagi turbin angina paksi mendatar. Bentuk aerofoil dipilih adalah mengikut piawaian National Advisory Committee for Aeronautics (NACA) siri lima digits, iaitu NACA 63-415. Bilah biasa dan bilah berslot ini dibentuk berdasarkan bentuan aerofoil NACA 63-415. Metodologi kajian ini termasuklah menggunakan perisian pemodelan rekaan untuk mencipta bilah turbin angin, menggunakan perisian dinamik bendalir komputasi untuk mensimulasikan aerofoil dua dimensi serta membentuk prototaip untuk diuji dalam terowong angin litar terbuka. Dalam ekspeimen ini, bilah-bilah dihasilkan dengan menggunakan percetakan 3D. Keputusan pekali lif dan seretan antara dua bilah ini telah didapati secara eksperimen dan berangka. Dalam simulasi, keputusan pekali lif yang tertinggi bagi bilah berslot telah mencapai nilai 0.2799 atau 42.8% lebih tinggi daripada bilah biasa. Malah, pekali seretan maksimum untuk bilah berslot juga agak tinggi, iaitu 0.04022 berbanding dengan pekali seretah bilah biasa yang hanya mencapai 0.01111. Pretasi aerodinamik keseluruhan bilah berslot lebih rendah daripada bilah standard. Di samping itu, keputusan eksperimen telah menunjukkan nilai pekali lif yang tertinggi bagi bilah berslot adalah 0.2763. Manakala bilah standard hanya sikit berbeza dengan bilah berslot, iaitu nilai pekali lif yang maksimum adalah 0.2600. Pekali seretan maksimum bagi bilah berslot pula adalah 0.4341 berbanding dengan bilah biasa yang hanya menunjukkan nilai 0.130.

Abstract (BI)

The exponentially growth of wind energy installations around the globe in the decade has shown of the importance role of renewable energy in our community. The optimisation of wind turbine technology is essential in term of increasing the feasibility of costs, impact and productivity as the growing global demand on wind energy production. The optimised topology design of wind turbine blade is expecting to overcome the problem of relatively low wind speed exhibits in Malaysia in order to meet the requirement of utility-scale wind power plant. The current works include the development of unconventional slotted blade of three-blade arrangement horizontal-axis wind turbine. The aerofoil shape is chosen according to National Advisory Committee for Aeronautics (NACA) standard of 5 digit series. In this case, the referencing aerofoil shape is NACA63-415. The slotted blade is also created based on the previous research on the slotted flap on the aerofoil. The designing methodology of this study is first using computer aided design modelling software to develop the model, followed by utilizing a computational fluid dynamics software to simulate a two-dimensional aerofoil. In the experiment, the blades are produced by using 3D rapid prototyping and tested in an open-circuit wind tunnel. The comparison lift and drag coefficient between improved design and standard blade are carried out experimentally and numerically. The numerical results show that the lift coefficient of blade been improved with achievable of maximum value, 0.2799 or 42.8% higher compared to standard blade. Simultaneously, the drag of slotted blade also increased to a maximum value of 0.04022 compared to standard blade of 0.01111. The overall aerodynamic performance of slotted blade is lower than standard blade due to lower lift to drag coefficient ratio. Additionally, for experimental results, the maximum lift coefficient of slotted blade 0.2763. For standard blade, the maximum lift coefficient is 0.2600 which slightly lower than slotted blade. Maximum drag coefficient of slotted blade is 0.4341 in contrast with standard blade coefficient that is 0.130.

Chapter 1 : Introduction

Wind power is one of the free renewable energy sources that convert the kinetic energy of the wind into electricity. Wind turbine is a growing worldwide renewable energy to meet the global demand on alternative energy sources. Extensive researches and developments of wind turbine energy over the decades emerge into some very innovative designs. The optimisation of wind turbine design is an important context in increasing its feasibility in term of cost, impacts and productivity.

A wind turbine is generic term for machines with rotating blades that convert the kinetic energy of wind into useful power. A horizontal axis wind turbine has advantages such as low cut-in speed and easy furling. It have relatively high power coefficient. The wind turbine blades are the main part of the rotor. Extraction of energy from the wind depends on the design of the blade. In this study, optimization of horizontal axis wind turbine blade will solely focused on the structural of the blade.

1.1 History of Wind Energy

The presence of utilization of wind energy was dated back to ancient time where human harnesses wind for sailing of ships and boats. During the era of 500-900 B.C., Persians employed wind energy conversion into useful mechanical power by using windmill to grind grains. The windmill, which once flourished along with the water wheel as one of the two prime movers based on kinetic energy of natural resources. Those windmill were vertical machine having sails made with bundles of reeds or wood. The grinding stone was attached to the vertical shaft. By the 13^{th} century, grain grinding mills were popular in most of Europe. France adopted this technology by 1105 AD and the English by 1191 AD. In contrast with horizontal axis Persian design, European mills had horizontal axis. These windmills reached America by mid-1700.

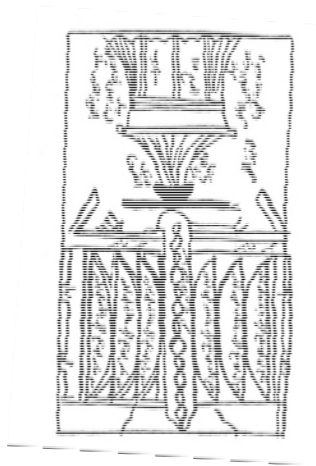

Figure 1.1: A Persian vertical-axis windmill in Sistan, according to al-Dismashqi, c. A.D. 1300. The earlier windmill design on record. Grinding stoned are above the rotor with its bellying cloth sails. The walls have opening to let the wind in and out [1].

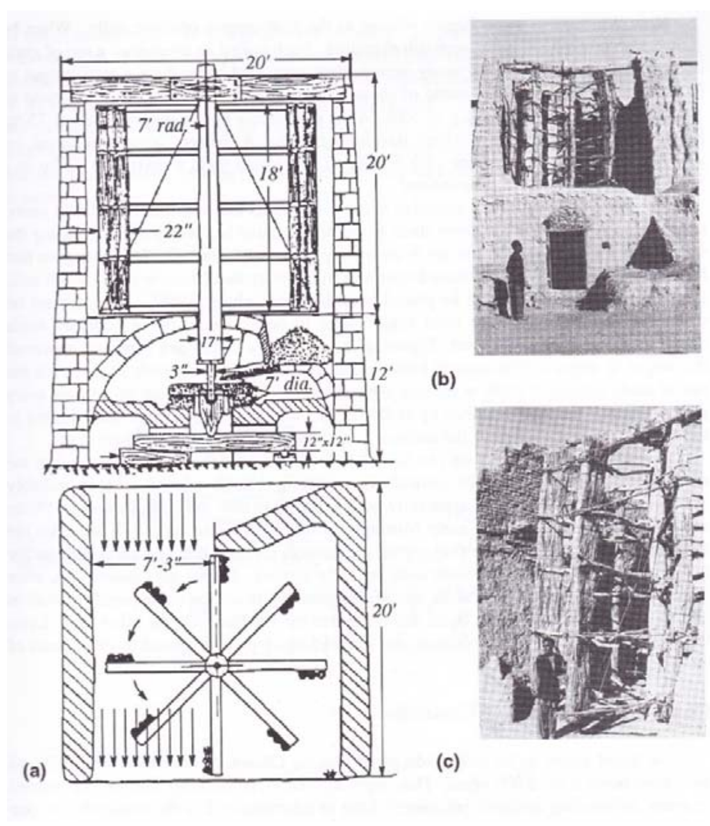

Figure 1.2: An existing windmill of Persian type in Neh. (a) The millstones are now below the rotor and the sails are bundle of reeds. (b) A general view of the downwind wall of the mill. (c) Close-up view of the reed sails[1].

At the start of medieval era, new advancements were made in the functionality of wind turbine, water pumping windmill, which is still considered as one of the most successful application of wind power was created. Later, American multi bladed wind turbine appeared in the wind energy history by the mid-1800. A relatively small rotor, ranging from one to several meters in diameter, was used for water pump application. The primary motive was to pump water from a few meters below the surface for agriculture uses. Windmills reached its apogee of utility in the seventeenth and eighteenth centuries. However, its use began to progressively decline when the thermal energy from combustion of fuel uses as prime movers took precedence. [1]

Figure 1.3: Some of many designs of American windmill, which was used for water pumping[1].

Nevertheless, the windmill persisted through the industrial revolution. Close to 1900 century, the era of wind electric generators was began. In 1890, the first specifically electricity generation designed modern wind turbine was constructed in Denmark. During the same period, in 1888, an enormous wind electric generator, named Brush windmill, which having 17m 'picked fence' rotor was built in Cleveland, Ohio. It was named after its inventor and builder, Charles F. Brush. A speed-up gear box was introduced in the design for the first time. This system operated for 20 years generating rated power of 12kW of DC power for changing storage batteries. [2]

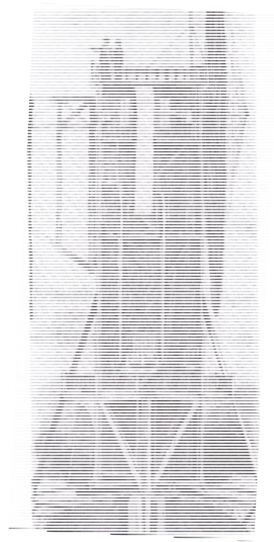

Figure 1.4: The Brush windmill built in 1888 in Cleveland, Ohio[2].

More systematic methods were adopted for the engineering design of turbines during this period. With low-solidity rotors and aerodynamically designed blades, these systems gave impressive field performance. By 1910, several hundreds of wind turbines were supplying electrical power to villages in Denmark. By about 1925, wind electric generator became commercially available in American market. Similarly, two and three bladed propeller turbine ranging from 0.2 to 0.3kW in capacity were available for charging batteries.

Turbines with bigger capacity were also developed during this period. This first utility-scale system were installed in Russia in 1931. A 100-kW 30-m-doameter Balacava wind turbine was installed on the Caspian seashore, which ran for two years and generated roughly 20,000kW electricity. Experimental wind plants were subsequently constructed in other countries like United States, Denmark, France, Germany and Great Britain.

Figure 1.5: The 100-kW,30-m diameter Balacava wind turbine in 1931. It was the first interconnected with AC utility system [2].

Some interesting design of wind turbine were experimented during this period. Darries G.J.M, a French engineer, put forth the design of Darrieus turbine in 1920. In contrast with popular horizontal axis rotors, Darrieus turbines had narrow curved blades rotating about its vertical axis. During the same period, Julius D. Madaras invented turbine working on Magnus effect. Magnus effect is basically derived from the force on a spinning cylinder placed in a stream of air. Another significant development at this time was the Savonius rotor in Finland, invented by S.J. Savonius. This rotor was made with two halves of a cylinder split longitudinally and arrange radially on a vertical shaft.

Intensive research on the behaviour of wind turbines occurred during 1950's. The concept of high tip speed ratio-low solidity turbines got introduced during this period. In the later years, research and development on wind energy are seen intensified. A few innovative concepts were proposed such as cortex turbine, diffuser augmented design, Musgrove rotor etc. Prototypes of these were constructed and tested. However, only the horizontal axis propeller design could emerge on a commercial scale.

1.2 Problem Statement

Malaysia highly depends on three major fossil fuel namely coal, natural gas and crude oil for power generation. In 2008, the primary energy supply, i.e. fossil fuel contributed total of 96.9% and only 3.1% contributed by hydropower. Crude oil and natural gas serves as a dominated energy supply in Malaysia that significantly contributes to greenhouse gases emission. Total of 64Mtoe of energy consumed in 2008, while back to 1990, it is only 10.3Mtoe of energy sources consumed. It indicates a trend of rapid growth of energy consumption in Malaysia. In the near future, fossil fuel will be facing the problem of serious shortage has triggered to explore new alternative energy as sustainable energy sources. [3]

Malaysia situated in Southeast Asia, with totalling up to 4675km of coastline. Wind energy would be one of the potential alternative energy source to be implemented. Despite Renewable Energy Act 2011 (Act275) was introduced and passed in the Malaysia parliament for implementation in 2011, however, wind energy has yet to attain recognition as an eligible renewable energy within Malaysia Renewable Energy Act [4]. In Malaysia, an annual average wind speed is about 2 to 3m/s which is very low and inconsistence[5]. In fact, annual average wind speeds more than 4 m/s are required for small wind electric turbines. Meanwhile, utility-scale wind power plants require minimum average wind speeds of 6 m/s at the hub height. In other words, Malaysia annual average wind speed is far too low to meet the requirements[6].

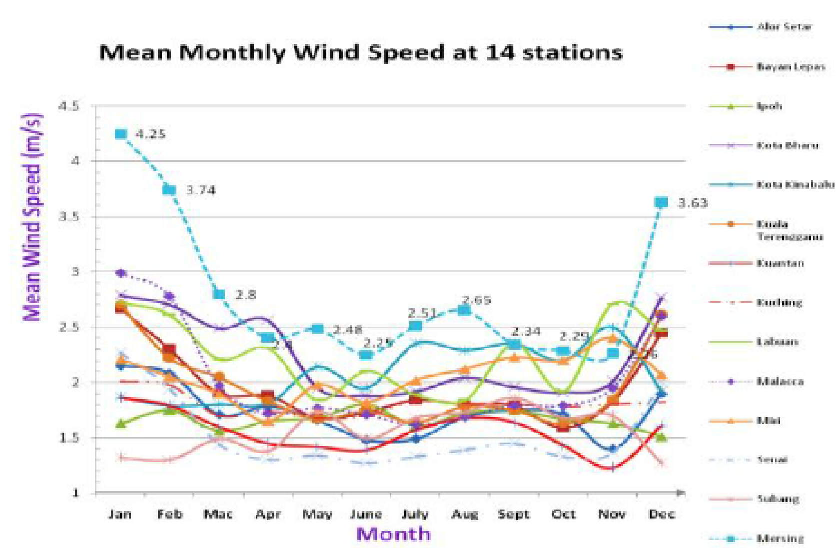

Figure 1.6: Monthly mean wind speed at 14 stations in Malaysia [7].

In order to establish wind energy harvesting system that is economically feasible in Malaysia, an enhancement of the aerodynamic performance of the wind turbine is important in this context. Optimisation of blade design is one of the options to increase the overall wind turbine performance. An optimization of wind turbine blade will solely focused on its structural of the blade. In this study, application of slotted aerofoil on wind turbine blade is proposed to overcome the current problems. It is expected the slotted wind turbine blade will improve lift-to-drag ratio and lift coefficient. At the end of the study, the optimum slot configuration will be presented.

1.3 Objectives

The objectives of this study is:

1. To design and propose an optimum slot configuration for wind turbine blade.
2. To investigate computational and experimental study on aerodynamic characteristic of slotted horizontal axis wind turbine blade design.

1.4 Scope of Work

This research involves design, fabrication, experimentation, simulation and analysis of the results. In the beginning of design stage, the selection of type of wind turbine as one of the essential measure for commercial-scale wind power generation. By choosing the suitable aerofoil standard and rotor diameter, the development of 3D model using computer-aided design (CAD) program with a standard blade and a unconventional topology slotted blade.

The numerical investigation of the aerodynamic characteristics of blade will be execute with the 2D side-view of the two designs produced for the simplicity for the comparison. Apart from that, the experimental of wind turbine blade will be prepared by fabrication of the blade. The fabrication stage is subdivided into rapid prototyping of the model and machining of the metal holder. The high precision of the production is crucial for the determination of the aerodynamic characteristics of the model. Two type of blades are fabricated with appropriate width so that fitted in the wind tunnel. It will test in a wind tunnel to obtain the aerodynamic performances of respective wind turbine blades.

1.5 Thesis Outline

This thesis comprises of five chapters.

Chapter 1 shows the introduction part which explains the research background and problem statement of this research and an outline of the dissertation.

Chapter 2 represents the literature review of this thesis which discuss in details on the literature review of the general information about global trend of wind energy, advantages and types of wind turbine, aerofoil as well as type of flaps.

Chapter 3 denotes the preparation for the numerical and experimental methods including the computation of blade geometry, computer-aided design of the blade model, experimental procedures and simulation procedures.

Chapter 4 discusses on the results obtained from the research. Elaboration on the problems encountered during experiment are also highlighted.

Chapter 5 summarizes the highlights of the research and formulate the overall conclusion of the project. Suggestions and recommendation for future studies are also included in this chapter.

Chapter 2 : Literature Review

In this chapter, the importance of the wind energy will be evaluated with its global growth rate trend in recent decades. Types of wind turbines are described and compared with its efficiency. The shape of blade, also formerly known as aerofoil will be reviewed to discuss its suitability for the design. Understanding different kind of the flaps and leading edge also helps in designing unconventional topology of the blade.

2.1 Global Trend in Energy Production

Global population grows at a very fast pace over the decades. The rapid advancement and development of technology has resulting in high demand in energy. The worldwide strong economic growth over the years, particularly in Asia has causes the demand in energy. With this trend prevailing, the global demand would increase considerably by 48% between 2012 and 2040 [8]. The global demand is met from variety of sources. In 2015, world energy production was 13790 Mega tonnes of oil equivalent (Mtoe), fossil fuels (coal, oil, natural gas) meet around 81.7% of the needs. Nuclear energy is shared around 4.9%. Meanwhile hydro energy accounts for 2.4% and nuclear is 4.9 %. Renewable sources such as wind, solar thermal, solar PV, geothermal, kept on expanding at a fast pace. But it still accounted less than 2% of global energy production[9].

The fact that fossil fuels are finite resources and will be completely exhausted one day or the other. The proved reserves of coal are only 566 Gtoe. Even at the current consumption rate of 2.26 Gtoe per annum, the proven coal reserve is sufficient only for the next 250 years. Reserves of oil and natural gas also face similar situation [2]. Not forgetting the environment impact causes by fossil fuel power plants add another dimension to the problem.

The effect of conventional fossil fuel resources rose the needs rapid development of renewable energy sources. The substantially rise of renewable energy expected to be achieving at least 55% in gross final consumption in 2050 [10]. According to Global Wind Energy Council (GWEC), the global cumulative installed wind capacity was increased from 23900MW in year 2002 to 486749MW in year 2016 [11]. The current trend of exponential growth rate of wind power production shows that the massive potential of wind industry in the near future.

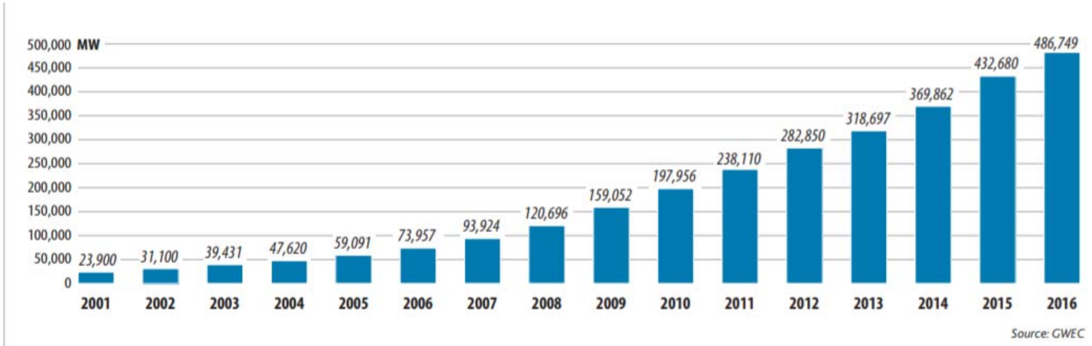

Figure 2.1: Global cumulative installed wind capacity from 2001 to 2016[11].

2.2 Advantages of Wind Turbine

Sustainable energy sources like wind energy are the great environmental friendly and economically viable alternative energy sources. Renewable energy sources present many benefits. They offer clean, uninterrupted, environmental impact-free electrical energy technology. Wind turbine technology act as one of the alternative renewable energy source. It is capable of generating greater amount of electrical energy with zero greenhouse effect compared to other energy generating scheme such as solar cell, tidal wave, biofuel, hydrogen, biodiesel, and biomass technologies [12].

Every energy source (coal-fired generation, nuclear power, hydraulic turbines, tidal waves turbines, geothermal and hydrothermal energy sources, bio fuel, conventional diesel generators and wind turbines) suffers from certain drawbacks. Coal fired- power produce harmful polluting gases and aerosols. Nuclear Power plants require heavy initial investment and present radiation dangers. Hydro-turbine installation require water reservoirs to ensure constant water pressure, and tidal wave turbines required ocean waves with specific characteristics available primarily in Portuguese coastal regions. Geothermal and hydrothermal energy sources require low- and high- temperature underground regions to harness energy sources. Biodiesel power sources required large supplies of raw materials.

Wind turbine does not require frequent or intermittent maintenance or employment of operations personnel. Thus, no maintenance or operation cost are incurred. The technology essentially offers home-made electrical energy and off-grid living, which is not readily possible with other technologies. Despite these benefits, the shortcoming of wind turbines is the damage to its tower structure or housing caused by strong winds may necessitate costly repaired or maintenance.

2.3 Classification of Wind Turbine

Wind turbine nomenclature has evolved during the past several decades. The typical modern wind turbines classified into two categories based on their rotate orientation, i.e. horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). HAWT have their axis of rotation horizontal to ground and almost parallel to the wind stream. Most of the commercial wind turbines fall in this category. Likewise, the axis of rotation of VAWT is vertical to the ground and almost perpendicular to the wind direction.

HAWT can further classified as upwind wind turbines and down wind turbines based on the rotor configurations with respect to the wind direction. Upwind turbines have their rotor facing the wind directly. They have no problem with tower shadow as the wind stream passes the rotor first. The drawback of the upwind rotor is yaw mechanism is essential in this design to ensure the rotor swept area facing the wind. In contrast, downwind turbines do not necessary need and additional mechanism for keeping them in line with the wind. The blades are built in high flexibility to bend in strong winds which reduces the swept area and subsequently reduces the wind resistance. Most of the modern wind turbines adopt upwind design configurations.

Typical VAWT are Darrius, Savonius, Solarwind, Helical, Noguchi, Maglev and Cochrane wind turbine. VAWT can receive wind from any direction. Therefore complicated yaw mechanism can be eliminated [13].

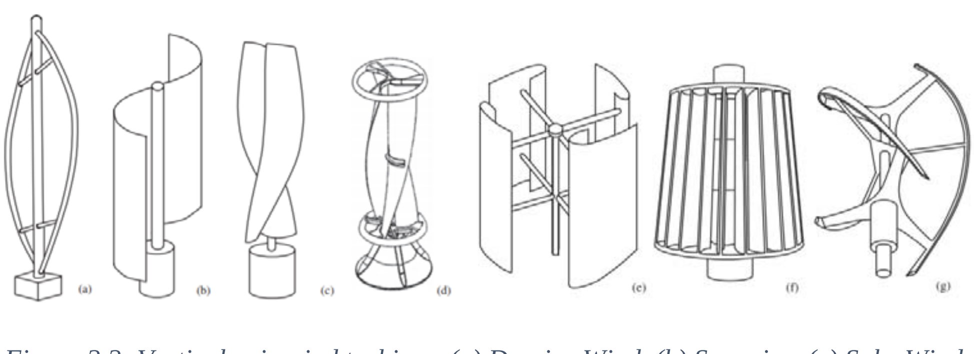

Figure 2.2: Vertical axis wind turbines, (a) Darrius Wind, (b) Savonius, (c) SolarWind, (d) Helical, (e) Noguchi, (f) Maglev, (g) Cochrane[13].

The principal subsystems that make up the total wind energy conversion system are the rotor, power train, nacelle structure, tower, foundation and the ground equipment station. HAWT mounted gearbox and electrical generator over the tower.

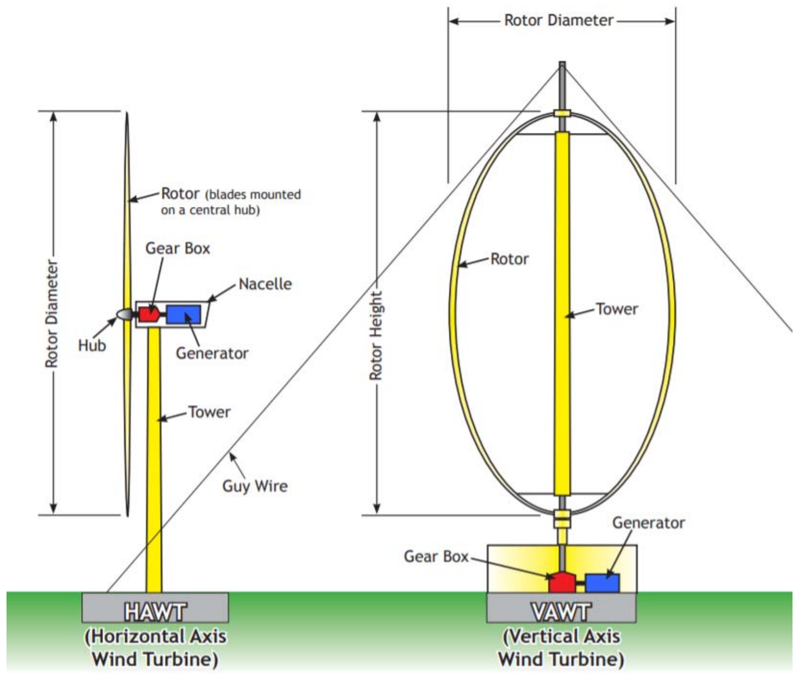

Figure 2.3: The principal subsystems of wind turbines. (Source https://teachergeek.org/wind_turbine_types.pdf)

2.4 Horizontal Axis Wind Turbine

Horizontal axis turbines display distinct advantages such as low cut-in speed and easy furling. In general, they have relatively high power coefficient. The variable blade pitch which gives the blades optimum angle of attack. The angle of attack manually controlled to maximize the wind energy collection. The tower height also can be adjusted which allows access to stronger magnitude of wind in sites [14]. Depending on the number of blades, horizontal axis wind turbines can be further divided into single bladed, two bladed, three bladed and multi bladed. One bladed wind turbines exist and it able to save cost of blade materials. It has minimum drag losses. However one bladed design is not very widespread commercially because it required a counter weight to place opposite the rotor blade will causes visual flickering effect.

Two bladed wind turbines are often downwind installation. Two bladed wind turbines have the benefit of materials cost saving and weight reduction. However its aerodynamic efficiency is lower than three bladed wind turbines due to it require higher rotational speed to yield same energy output. A complex teetering hub is essential for one and two bladed designs which induces less cost effective in these two designs [15].

Three bladed HAWT has smooth operation that they are more stable as the aerodynamics load is relatively uniform. Thus most of the modern commercial wind turbines used for electricity generation have three blades. This design is commonly called classical Danish concept and tend to be a standard against other evaluated concepts. These three bladed wind turbines that dominate current markets operate at high tip speed-to-wind speed ratio ranging from 5 to 7 and with rotational speeds of 10 to 30 revolutions per minute (RPM) [13].

HAWT has their design more complex and expensive due to the generator and gearbox are mounted at in line with rotor. The need of the tail or yaw drive to orient the turbine towards wind has also increase its complexity on design. Landscape appearance may affected wind turbine farm as the enormous height of the turbines obtrusively visible across large areas. The structure of HAWT suffer from fatigue and structural failure due to long term cyclic load exert by turbulence.

2.5 Vertical Axis Wind Turbine

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Darrieus rotor, named after its inventor Georges Jeans Darrieus, works due to the lift force generated from a set of airfoils. It more commonly called “egg beater” turbines. This typical type configuration help in minimize the bending stress experienced by the blades. Darrieus rotor works at high tip speed ratio which makes it attractive for wind electric generators. The largest drawback of Darrieus design is the requirement of the external force in starting the rotation of rotor. On top of that, the rotor can only produces peak torque twice per revolution.

The Savonius wind turbine, with high solidity, invented by S. J. Savonius, is a vertical axis rotor consisting two half elliptical arrange in ‘S’ shape. The principal driving force of Savonius rotor is drag force. The concave side of the elliptical shape is facing more drag force than the convex side. The performance of the Savonius rotor is relatively low. Some experimental rotors have power coefficient up to 35%. They work at low tip speed ratio which favourable for high torque-low speed application like water pumping [2].

VAWT produce fluctuating power output due to the changes of both the angle of attack of the aerodynamic surface and local dynamic pressure. As the wind speed is higher with elevation, VAWT located at the ground indicates its lower power efficiency as compared to HAWT with same swept area[12].

2.6 Comparison Performance between Two Propulsion Mechanisms

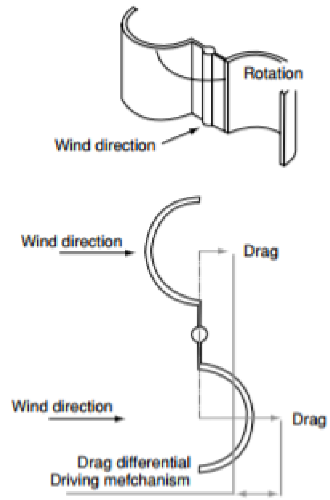
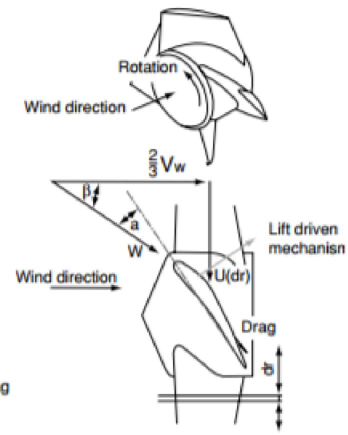
Energy extracted from the wind turbine is extremely important in determining the maximum efficiency of the wind energy. Power available from the wind is

$$P = \frac{1}{2}\rho A V^3 \quad (1.1)$$

Where ρ is air density, A is swept area and V is representing air velocity [17].

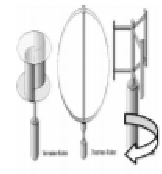
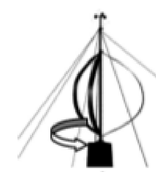
Maximum achievable theoretical efficiency is highly depending on the method of propulsion. As discussed earlier, horizontal axis wind turbines have higher power efficiency than vertical axis wind turbines. Wind turbines that rely on drag force are insufficient power producers as their tip speed ration cannot exceed one. This is because the relative velocity of wind is reduced as the rotor speeds increases. Thus, based on equation (1.2), power extracted is decreased. In contrast, propulsion that utilizes aerodynamic lift can generate a greater wind energy due to aerodynamic lift can generate at a narrow corridor of varying angles normal to wind direction. In other words, the relative wind velocity will not decrease in rotor speed. The comparison of maximum theoretical efficiency is shown in Table 2.1.

Table 2.1: Two mechanisms of propulsion compared [17]**.**

Propulsion	**Drag**	**Lift**
Diagram		
Relative wind velocity	$= WindVelocity - BladeVelocity$	$= \sqrt{\frac{2}{3}WindVelocity^2 + bladeVelocity(dr)^2}$
Maximum theoretical efficiency	16%[4]	50%[6]

The minor losses accounted from tip losses, wake effects, drive train efficiency and blade shape simplification losses lead to virtually not achievable of the maximum theoretical efficiency. Therefore, practical efficiency harvested over the centuries based on various kind of wind turbines are list as Table 2.2.

Table 2.2: Modern and historical rotor design and its peak efficiency [17].

Ref no.	Design	Orientation	Use	Propulsion	*Peak efficiency	Diagram
1	Savonius rotor	VAWT	Historic persian windmill to modern day ventilation	Drag	16%	
2	Cup	VAWT	Modern day cup anemometer	Drag	8%	
3	American farm windmill	HAWT	18th century to present day, farm use for pumping water, grinding wheat, generating electricity	Lift	31%	
4	Dutch windmill	HAWT	16th century, used for grinding wheat	Lift	27%	
5	Darrieus rotor (egg beater)	VAWT	20th century, electricity generation	Lift	40%	
6	Modern wind turbine	HAWT	20th century, electricity generation	Lift	Blade qty / efficiency 1 43% 2 47% 3 50%	

2.7 Aerofoil

An aerofoil is the shape of a wing, blade or sail. Aerodynamic force produces through moving the aerofoil-shaped body through a fluid. National Advisory Committee for Aeronautics (NACA) develops a system as known as NACA airfoil to describe the shape of aerofoil using a series of digit following the word “NACA”. The family of NACA airfoil series including 4-digit, 5-digit, modified 4/5digit and 6 series describe the camber of the mean-line of the aerofoil section as well as the section’s distribution along the length of aerofoil. Other standards also provided for wind turbine specific aerofoils such as Delfi University, LS, SERI-NREL and FFA and RISO.

The shape of aerodynamic profile is decisive for blade performance. The NACA 44 series were used on older Bonus wind turbines (up to and including the 95kW models). The profile has good all-round properties and it is giving a good performance curve as well as good stall. It is intolerant of minor surface imperfections, such as dirt on the blade surface. However, NACA 63 series developed during 1940's which used in newer Bonus Wind Turbines (from 150kW models), has minor differ properties than NACA 44 series. NACA 63 profile has better power curve in the low and medium wind speed ranges, but drops under high wind speeds operation. Similarly, this profile is sensitive to dirt on surface [18]. NACA 63-415 is designed for use for aeroplanes as well as wind turbine. It shows sensitivity to leading edge roughness with operational Reynolds numbers around 3.0 million [19], [20]. Stall known as an aerodynamic phenomenon which the boundary layer separated at the tip rather further down the aerofoil causing a wake to flow over the upper surface drastically reducing lift and increasing drag forces. This usually happens during large angles of attack.

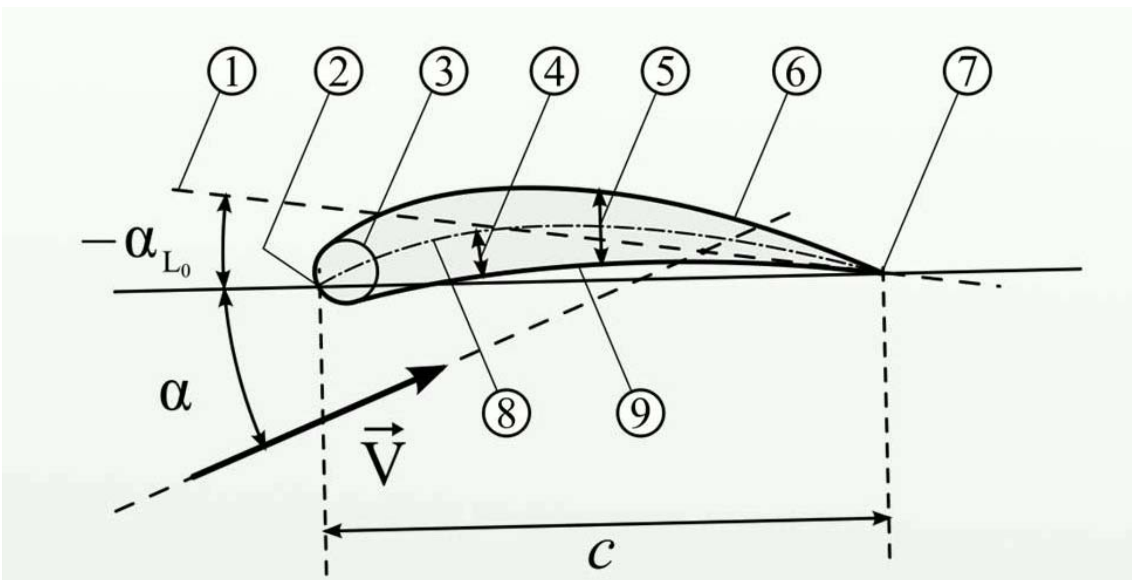


Figure 2.4: Profile geometry of NACA airfoil, (1) Zero lift line, (2) Leading edge, (3) Nose circle, (4) Max. thickness, (5) Camber, (6) Upper surface, (7) Trailing edge, (8) Camber mean-line, (9) Lower surface. (Source: https://en.wikipedia.org/wiki/NACA_airfoil)

Table 2.3: The aerofoil requirements for blade regions.

Parameter	Root	Blade position (Fig 2) Mid span	Tip
Thickness to chord ratio (%) (($\frac{d}{c}$) Fig 2)	> 27	27–21	21–15
Structural load bearing requirement	High	Med	Low
Geometrical compatibility	Med	Med	Med
Maximum lift insensitive to leading edge roughness			High
Design lift close to maximum lift off-design		Low	Med
Maximum CL and post stall behaviour		Low	High
Low Aerofoil Noise			High

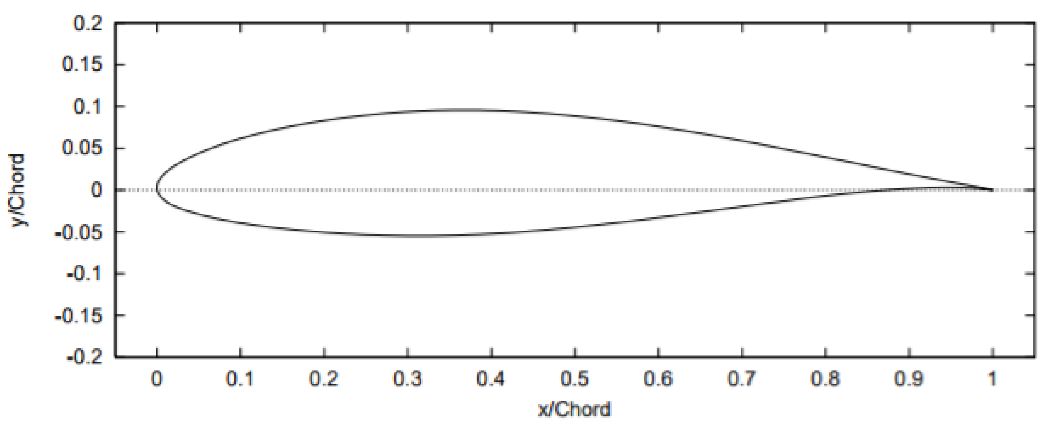


Figure 2.5: NACA 63-415 aerofoil.[21]

Due to typical curvature of the blade, air passing the upper side has to travel more distance per unit time than the lower side. The air particles at upper layer move faster. According to Bernoulli theorem, this should create low pressure region below the aerofoil. The pressure difference would results in a force. The component of force perpendicular to the direction of undisturbed flow is called the lift force, L. The force parallel to the direction of the undisturbed flow is named drag force, D.

Lift force,

$$L = C_L \frac{1}{2} \rho A v^2 ----(1.2)$$

Drag force,

$$D = C_D \frac{1}{2} \rho A v^2 ----(1.3)$$

Where ρ is the density of air, A is the control area, and v is the air velocity

2.8 Slotted Flap

There are many high-lift devices available in current aeronautical technology application. The major classification of high-lift devices are divided into flap and leading edge slat. Flaps are the most common high-lift devices used on aircraft. There are four common types of flaps: plain, split, slotted, and Fowler flaps. Slotted flap is one of the most popular flap. Slotted flaps increase the lift coefficient significantly more than plain or split flaps due to the high energy air is ducted to the flap's upper surface. It able to accelerate the upper surface airflow and hence delay the boundary separation [22].

The research based on improvement of aerodynamic characteristics of wind turbine aerofoil under stall conditions was carried out by Belamadi [23]. An extensive 2D-numerical study based on different slot's location on S809 aerofoil has been done to analyse the effects of slot's location, width and slope. It shows that it is doesn't necessarily improve aerodynamic characteristics by adding slot. The best configurations at different angle of attack are sorted out.

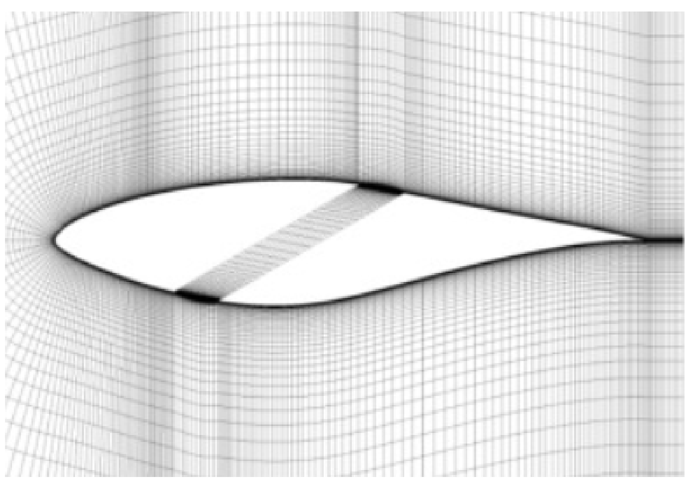


Figure 2.6: Aerofoil S809 with slot.[23]

A review of aerodynamic performance of NACA 4412 aerofoil on horizontal axis wind turbine blade was carried out by M. Ibrahim and the team [24]. The results of the leading edge slotted blade showed a sharp increase in the generated power at a lower wind speed when compared to the standard straight blades. The difference between the two designs in power generation can be clearly observed. For the same 1000 rpm rotation speed, the slotted blade was able to generate up to 60% more power at a lower cut-in speed compared to the straight blade.

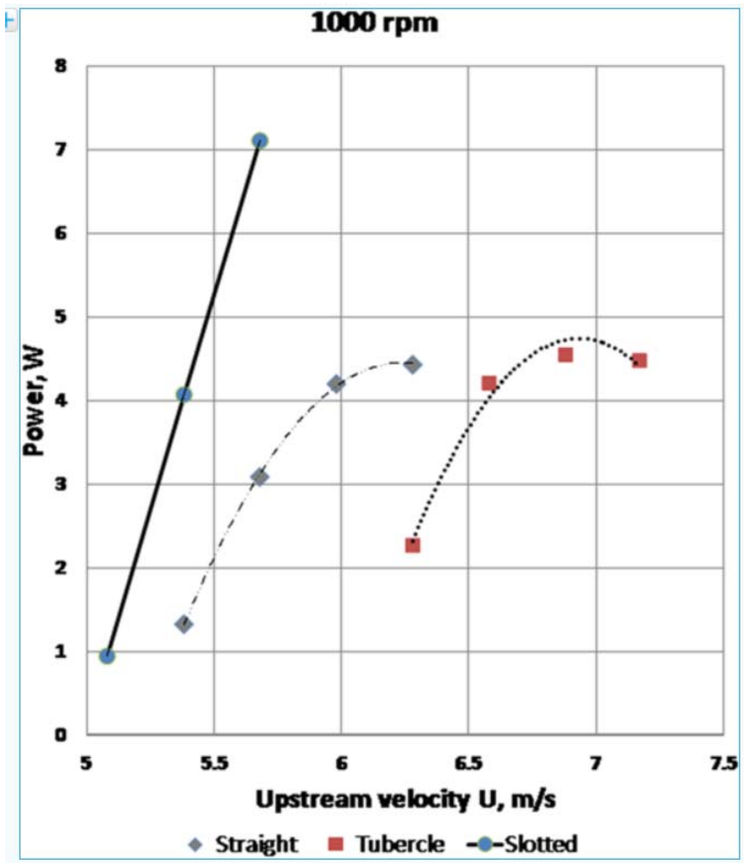


Figure 2.7: Power generated by cut-in wind speed of different type of blades [24].

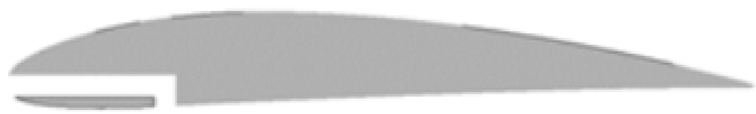


Figure 2.8: Design of leading edge slotted blade of NACA 4412 by M. Ibrahim [24].

There are numerous types of slotted flap are classified by their geometry. The primary classification is the number of slots. The single-slotted flap is the simplest and most vastly used type.

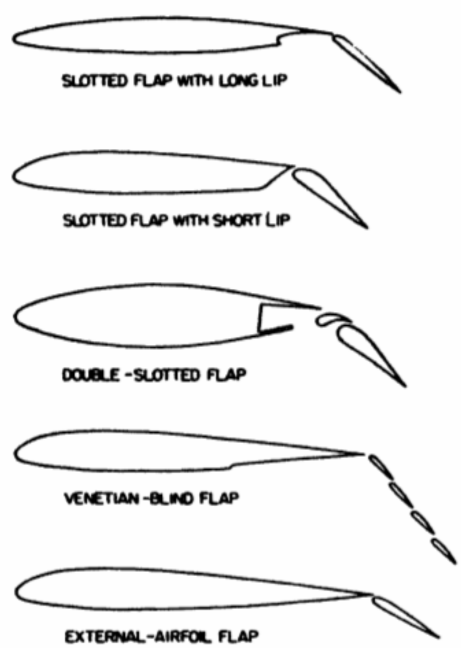


Figure 2.9: Several type of slotted flaps [25].

It is important to realize that if the slot is not efficient it may be worse than no slot at all, as the flow through it may then stimulate rather than suppress flow breakaway over the flap. It is this tendency of a well-designed slot to suppress flow breakaway over the flap that gives the slotted flap its characteristic of low drag at small or moderate flap angles. The geometrical shape of the slot must be carefully considered if the desired increase is to be realized; for this reason it is difficult to give definite rules for the best position of the flap. Sharp edges at the beginning of the slot are to be avoided as much as possible on thick profiles, but thin profiles are less sensitive in this respect. If the suction side is bent round at the trailing edge in the direction of the upper side of the flap, there is often a favourable effect.

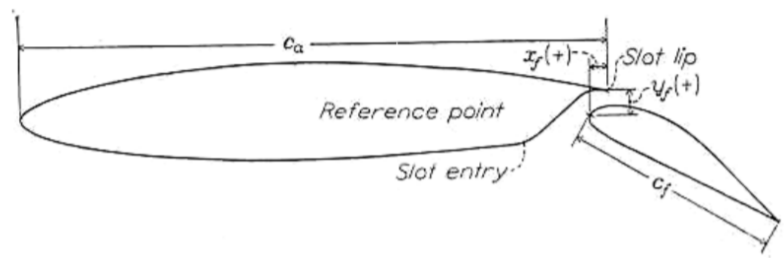


Figure 2.10: Typical single slotted flap configuration [26].

Although many experimental data of slotted flap aerofoils have been accumulated over the decades. An important consideration in design of slotted, particularly single slotted type, is the extent to which the flap moves aft as it is deflected. The movement of the flap may vary from a simple rotation about the fixed point to a combined rotation and translation that moves the leading edge of the flap to the vicinity of the normal trailing-edge position. Rearward movement of the flap requires an extension of the upper surface over some or all of the flap in the retracted position. This extension of the upper surface serves to direct the flow of air through the slot in the proper direction and is called the "lip."

The flow about a wing section with a deflected slotted flap is very complicated and no adequate theory has been developed to predict the aerodynamic characteristics. Thus, the best position of single slotted flaps are not well defined [25]. Maximum lift coefficient of slotted flaps are very sensitive to flap position, however, and optimum configurations cannot be predicted with any degree of accuracy [26].

One important parameter of single-slotted flaps is the chordwise position of the lip. Despite completely comparable data are not available for the configurations with varied positions of the lip, the maximum lift coefficients appear to increase as the lip position approaches the trailing edge for wing sections of moderate thickness. In the case of thin wing sections, especially of the NACA 6- series type, the flap thickness may become too small with a rearward location of the lip to permit favourable slot configurations under such conditions, the favourable effect on the maximum lift coefficient of moving lip toward the normal trailing-edge position may not be realized.

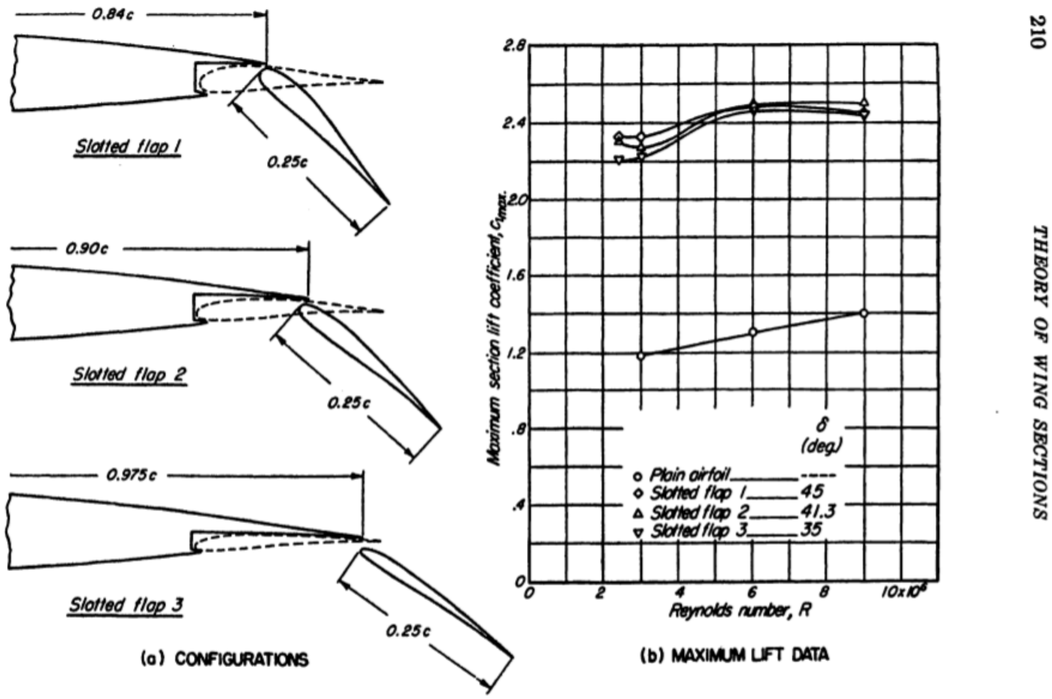


Figure 2.11: Variation of maximum section lift coefficient with Reynolds number for several slotted flaps on the NACA 65-210 wing section [25].

The maximum lift coefficient of the NACA 65-210 section are essentially the same for the lip position of 0.84c, 0.90c and 0.95c. The structural difficulties presented by a long thin lip extension and the mechanism necessary for the corresponding large rearward movement of the flap are such as to discourage the use of rearward locations of the lip.

The flap chords are normally fall within the range of 0.25c to 0.30c. Although NACA 23012 shows larger increments of lift coefficient are obtained with the larger chord flap, but the increased effectiveness is small. The slight increment of maximum lift coefficients do not appear to justify the structural difficulties encountered with such flaps.

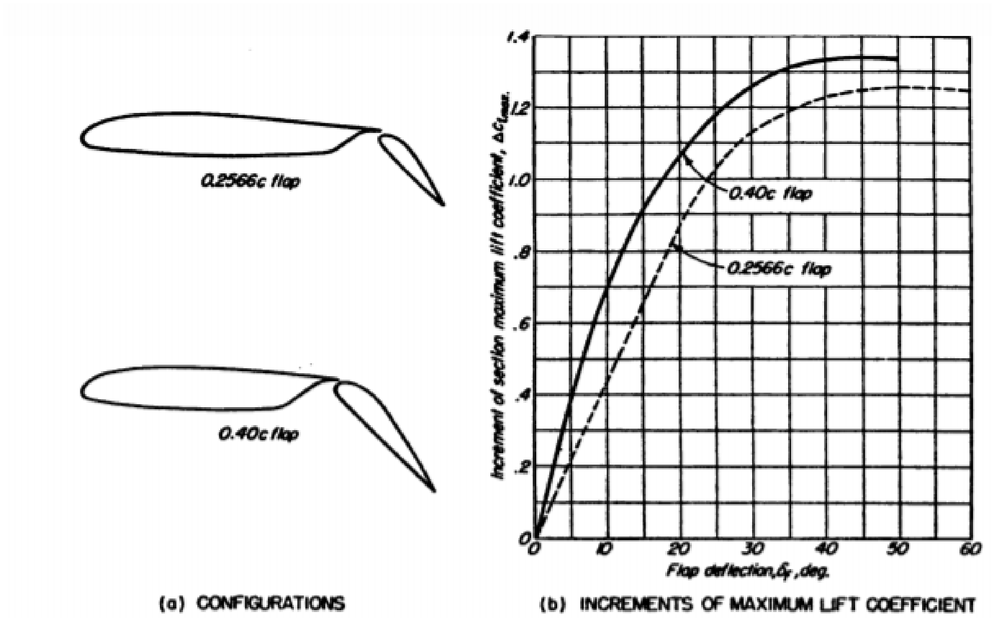


Figure 2.12: Effect of flap chord on increments of section maximum lift coefficient for the NACA 23012 wing section [25].

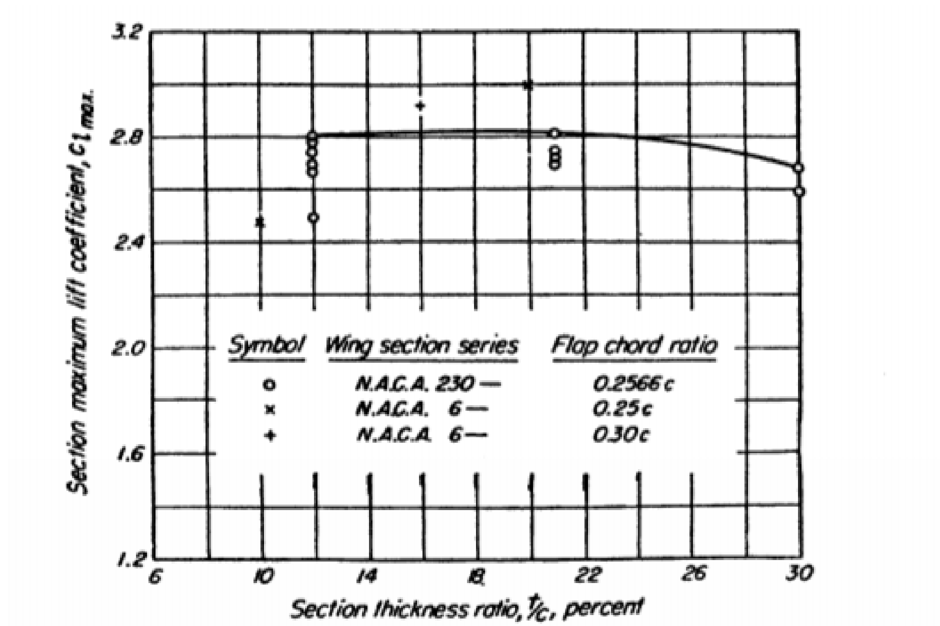


Figure 2.13: Maximum lift coefficients for various arrangements of slotted flaps [25].

A few limited data indicate the maximum lift coefficients obtainable for comparable slotted flaps on NACA 6-series wing sections. The maximum lift coefficients obtainable shows that 10% thick sections are appreciably less than those obtainable with thicker sections.