Fiber optics flow measuring techniques and feasibility study of its implementation as an angle of attack sensor and stall detector

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**NANYANG
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**FIBER OPTICS FLOW MEASURING TECHNIQUES AND
FEASIBILITY STUDY OF ITS IMPLEMENTATION AS AN
ANGLE OF ATTACK SENSOR AND STALL DETECTOR**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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SENSOR AND STALL DETECTOR**

SUBMITTED

BY

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**SCHOOL OF MECHANICAL AND AEROSPACE
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Abstract

There is a continuous demand to reduce the cost of energy from wind turbine generators. Active control techniques were found to achieve significant savings in energy production without demanding a huge setup cost. However, a successful active control requires sensing technique that is able to fulfil the key design requirements of a flow sensor to be placed near the blade tip of the wind turbine. The requirements of the velocity sensing design are lightning attraction issues and dust, high reliability, control accuracy and low cost - which the current techniques cannot fulfil. Therefore, with the motivation to drive the improvement of the wind measurement techniques forward, an optical fiber velocimeter was presented as a viable flow measuring device. By integrating the fiber optic flow measurement analytical model and active closed-loop feedback system, this project seeks to offer a potential viable method of velocity measurement.

Initially, proof of concept using optical fibers to measure wind velocity was established on a flat surface and it was verified on an aerofoil design. By varying the optical fiber insertion location on the aerofoil, two different fiber optic flow measuring techniques were created. The two different fiber optic techniques are able to bring promising results that could be applied to the two-dimensional flow field of the aerofoil for wind turbine application. Firstly, the fiber optics stall detector was designed to pitch the blade to the maximum Angle of Attack (AOA) before stall occurs. The second technique described the use of the optical fibers as an AOA sensor that can determine the angle of attack and to correctly pitch the blades to the optimum AOA. If the system permits, combining both the AOA sensor and the stall detector would provide a very robust system.

The results have shown that the AOA sensor was able to differentiate the AOA intervals and the stall detector was able to capture an increase in fluctuation during the stalling of the blade. With the support of these promising results, both application techniques have demonstrated their capabilities as sensors on an actual wind turbine. This report concludes that the fiber optics are prospective wind sensing techniques in the future but the technology requires further developments as suggested in the report's future work.

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Chapter 1

Introduction

1.1 Background

Wind turbine manufacturers are constantly trying to improve the performance of the wind turbines to decrease the cost of energy. This is especially critical during the reduction of production tax credits by various governments. There are several techniques to improve the energy production and to decrease the unit cost of power. One way is to improve the dollars per kilo watt hour is by increasing the size (radius) of the wind turbine rotors or by installing the turbine at higher altitude. The power generated is directly proportional to the square of the rotor diameter and cube of wind velocity which is generally stronger at higher altitude. Nevertheless, this in return introduces heavier design weight requirement, which eventually results in the increase of material and manufacturing costs, while posing additional logistical challenges during the wind turbine transportation and installation as well. Another method to use is by increasing the effectiveness of capturing the wind by providing an active pitching control, which is also known as smart rotor control [1] .

In a study by the National Renewable Energy Laboratory (NREL) on a test wind turbine, it was observed that the estimation of the angle of attack acting on the wind turbine blade has been “ a challenging and an essential area of inquiry” [2]. Amidst the numerous patent claims on the optimum control method, none has provided any viable means of obtaining local blade flow profile information [3, 4].

Besides the lack of a suitable flow measuring device to be used for wind turbines, the placement of the wind sensing device also poses a problem. To ensure efficiency of the wind turbine, the sensing device is responsible for the directing the blades into the wind. It was discovered that placing the anemometers at the rear of the nacelle causes the anemometers to be constantly affected by the turbulence generated by the nacelle body and the rotation of the turbine blade. Therefore, it is recommended to develop a local blade flow measurement technique that is installed at the blade tip so that the actual flow conditions are measured for the optimum pitching of the blades to obtain high power output and to reduce load on the wind turbine blades [1, 5].

The active control has been found to be able to improve energy production and to reduce load on the blades which can enhance the life of the blades [1, 5]. However, such designs use flow

measuring devices such as pitot static tubes [6], pressure taps [7] and sonic anemometers [8, 9] which have their drawbacks when placed on wind turbines especially near the blade tip. These measuring devices contain electronic parts which are electrically conductive and therefore increase the risk of damages by lightning strikes. In addition, pressure taps and pitot static tubes operate with orifices which are prone to dust accumulation. Since wind turbines are usually situated in remote wind farms, there has to be minimal maintenance works to reduce expenses. Hence, sensing equipments with long term reliability issues will not be suitable. The light detection and ranging (LIDAR) system which uses the laser doppler effect to achieve accurate remote sensing of the wind profile was also mentioned by researchers [10]. But the effects of the wind closer to the wind turbine are not known as LIDAR is not capable of sensing at the local blade flow measurement. Hence, there is a need for a measuring device which is able to measure the local blade measurement and also to be immune to the environmental conditions that the sensor will be subjected to.

Optical fiber (or fiber optics) was developed in the 1900s and has been extensively used in the telecommunication industry due to their low loss of signals during transmission over relatively long distances. Besides, they are used as sensors to measure temperature [11], strain [12], pressure and displacement by relating the change in wavelength, phase or intensity of signal in the fiber.

Recently, fiber optics is introduced in the area of condition monitoring to detect the strain on structures. In the area of wind turbines, fiber optics were embedded within the composite blades to determine the loads [13]. The aim is to reduce the load that the blades carry so that the blades would be able to last longer by using active load reduction through pitching [5, 14]. There were some developments on the use of the fiber optics for flow measurement [15, 16] but it was not deployed on the wind turbine blades. Fiber optics are known to be immune to electro-magnetic interference [15], which shows that it reduces the probability of lightning attraction issues and dust particles do not affect the operation of the fiber optics. Therefore, a novel technique of using the fiber optics as a local blade flow sensor is explored in this dissertation.

1.2 Design Requirements

As wind turbine is a gigantic structure (the modern 8 MW turbine is of 164m rotor diameter [17]), accessing to the top for maintenance or repair works can be extremely difficult and

costly. Therefore, wind sensing equipments that are placed near the blade tip have to satisfy the following design considerations:

1. Lightning attraction issues
2. Capable of accurately sensing the wind velocity.
3. Provide data such that it can deduce the correct angle of attack
4. High reliability throughout the design lifecycle of the equipments
5. Safety of the equipments
6. Ease of use and installation
7. Low cost

1.3 Objectives

The objectives of this project are:

1. To develop a novel flow measurement technique using optical fibre which can be applied on the wind turbines for optimum pitching of the turbine blades and improving the power production. The device is placed near the tip of the wind turbine blade to ensure maximum sensing capability and to overcome the limitations of the current existing techniques
2. To verify the simulation/numerical results against the experimental measurements.

1.4 Scope

The scope of the project includes the development of an optical fiber wind sensor, and applying it to *angle of attack (AOA)* and *stall* detection.

1.5 Report Layout

Chapter 1 briefly explains the importance of wind velocity sensing, sensor design requirements and the overall objectives of the work. Chapter 2 describes pertinent measuring flow techniques such as pitot static tube, mechanical anemometer and other flow measuring

system. Fiber optics flow measurement system is also introduced as an alternative means of flow measurement. The fiber optics sensor is next deployed as an angle of attack sensor and a stall detector. Chapter 3 presents the details the experimental setup followed by results and discussion in Chapter 4. Finally, Chapter 5 gives concluding remarks and scope for future work.

Chapter 2

Literature Review

In this chapter, a review of some common measurement techniques that have been mentioned in Chapter 1 will be presented. The drawbacks and strengths of these common measurement techniques will also be examined in greater detail and compared with the fiber optics measurement techniques. Some past fiber optics measurements methods will also be studied for better comprehension of the work done on fiber optics, followed by an illustration of improvements that can be accomplished in the techniques. Furthermore, different controls techniques and the close and open loop systems will be discussed to appreciate the optimum approach for flow sensing on wind turbines stated in Chapter 1. Finally, mechanics of fluid flow over a National Advisory Committee for Aeronautics (NACA) 63415 air foil are described to facilitate the appreciation of this project.

2.1 Flow Measurement Techniques

Since the invention of flow measuring devices, it has grown to become a very important tool for many different industries. In these industries, there is a constant need to monitor and understand the velocity of the fluid under any particular condition. For instance, in the aircraft industry pilots would need to know the air velocity so as to navigate safely to their destination. In the oil industry, the understanding of the flow in the pipe is also critical to their operations. Flow measurement instruments operate based on various physical properties and are categorized based on their response to the properties of the fluid flow or the behaviour of the fluid flow. The categories are namely mechanical flow meters, pressure based meters, sonic based flow meters, and laser doppler flow meters. These are a few of the many types of flow meters available, but the scope of the report will focus the types mentioned above, with illustration on the application in wind industry.

2.1.1 Mechanical Flow meter

The term mechanical flow meter refers to using moving mechanical parts in a specified medium to detect the flow speed. The first mechanical anemometer was first designed in 1450 by an Italian mathematician Leon Batista Alberti [18, 19]. Leon Batista Alberti invented a disk which had the ability to spin when struck by the wind. This disk was connected to a scale which would correlate the wind speed with the measured angle of displacement. It was

only in 1846 when a breakthrough improvement was made to the anemometer by John Thomas Romney Robinson. His design consisted of 4 cups attached to a central piece as shown in figure 2.1a. The cups are propelled by the wind and the wind velocity could then be determined by the amount of revolutions over a period of time. The basic 4 cup anemometer design has since evolved into many different designs but the fundamental principle behind the design of the anemometer remains unchanged till today.

Figure 2.1 a) Schematic of the mechanical anemometer [20] b) Actual mechanical anemometer [21]

The measurement of the rotational speed of the cups mounted on the radial spokes is conducted using encoders. As the wind flow across the cups, drag is produced which is used to turn the shaft that the cups are mounted on. The drag coefficient of the back of the cup is lower than the front due to its steam line profile [22]. When the four cups are aligned in a circular manner, the wind will hit the front of one cup and the back of the opposite cup. Due to the higher drag coefficient of the front of the cup, the turning torque will be in the direction of the wind [21]. The rotational speed of the cups is related to the wind speed by [16]:

$$U = A.f + B \quad (2.1)$$

where U is the wind speed, A and B are the instrument calibration constant that is calibrated in a wind tunnel, f is the frequency of the rotation. Therefore one would be able to calculate the average wind speed from measurement of the anemometer rotational speed.

Mechanical anemometers are considered to be one of the oldest flow measurement techniques with a history of more than 500 years. Despite this, they are still in use today because of their simple fabrication and design. Their simplicity contributes to low costs in comparison to other systems which require more sophisticated technology. As the design is relatively simple,

it is very reliable and is often used by metrological stations for wind data. Reliability enhanced mechanical anemometer are used to be deployed at the back of the wind turbine nacelle. However as technology advances, the deployment of the anemometer is slowly replaced by sonic anemometer and laser doppler anemometer systems.

Strengths aside, there are some factors which affect the accuracy of the measurements from the mechanical anemometer. The most dominant factor is the angular response of the anemometer. The cup anemometer could only accurately measure rotational speed when the direction of the wind is perpendicular to the central axis of the rotating cups [23]. Therefore it is more common to determine the average wind speed rather than instantaneous wind speed from the cup anemometer due to errors caused by its angular response. Another noticeable issue with the cup anemometer is the over speeding effect. This over speed effect is caused by the aerodynamic properties of the cup in which the cup tends to accelerate faster than its deceleration resulting in an over estimation of the wind speed. This effect is prominent in the middle wind speed range. Other factors which affect the accuracy of the measurements are the response length, cup size and calibration constant [23].

Although the mechanical anemometer is quite reliable, but it requires regular maintenance due to the rotating parts. The rotating parts will lead to wear and are prone to dust entrapments. The high chances of lightning attraction issues also poses another disadvantage to the mechanical flow meter.

Figure 2.2 A mechanical anemometer deployed on a wind turbine [24]

2.1.2 Pressure Based Flow Meter

Many different designs exist for pressure based flow meters. Some examples include the differential pressure flow meter, the venturi flow meter and the pitot static tube based on

Bernoulli's energy balance principle to determine the flow speed. The differential pressure flow meters and the venturi flow meters are only applied in internal flow.

Bernoulli's equation is based on the conservation of energy for inviscid and incompressible flow. It is applied to streamlines, where the total energy on any point along the streamline is constant throughout in a steady flow. The total energy is the sum of pressure, kinetic and potential energy [25] as,

$$P + \frac{1}{2}\rho V^2 + \rho gh = C \quad (2.2)$$

where P is pressure of air, ρ is density of air, V is velocity of air, g is gravitational acceleration, h is height, and C is a constant. The increase of flow speed would cause a decrease in pressure and vice versa as long as Bernoulli's equation is fixated on the same streamline.

One device that applies Bernoulli's principle in the measurement of air flow is the pitot static tube. The pitot static tube measures the local flow velocity by having two orifices, one in line with the tube and the other at the side of the tube. The orifice that is in line with the tube measures the total pressure as the flow velocity at the orifice equates to zero while the side orifice measures the static pressure. For a similar flow with same potential head, the generalised Bernoulli's equation (2.2) can be reduced to:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 \quad (2.3)$$

where $V_1 = 0$ due to non-slip properties, zero velocity at the wall.

$$P_1 = P_2 + \frac{1}{2}\rho V_2^2 \quad (2.4)$$

Thus equation (2.3) can be represented as,

$$V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho}} \quad (2.5)$$

Figure 2.3 shows a schematic diagram of the pitot tube. In order to determine the flow velocity, the pitot tube has to be in the flow field. The flow will flow into the two tubes and the transducer or a diaphragm would be able to determine the pressure difference between the

P_1 and P_2 . Due to the differential pressure, a force will be acting on the transducer which causes the transducer to generate signals. These signals can be directed to an output display to demonstrate the readings [25].

Figure 2.3 Schematic of pitot tube [26]

The pitot static tube is well established for its reliability and accuracy as long as it is regularly calibrated and maintained. Its ability to determine supersonic flow makes it widely used in aircrafts as an airflow speedometer. Pitot tubes are also commonly used in wind tunnels for flow measurement due to their accuracy and cost effectiveness as compared to other high accuracy measurement techniques like the sonic anemometer.

The success of the application of pitot tubes on wind turbines has been observed on a small scale laboratory level by the National Renewable Energy Lab (NREL) and other laboratory scale wind turbine [27]. However, there are no reports of such application on the actual large scale wind turbine. Due to the orifice's small size, dust blockage becomes an issue. Hence, regular maintenance is required to remove the dust particles trapped in the orifice. Currently, there are studies to assess the feasibility of pitot tubes on wind turbines. The pitot tube is usually made up of stainless steel or high grade metal as they are known for high strength. Being a highly conductive metal and the electronics for the transducer of the pitot tube would poses a critical lightning attraction problem due to its high elevation.

2.1.3 Sonic Anemometer

The sonic anemometer was first developed by a geologist named Dr. Andreas Pflitsch in 1994. Ultrasonic waves are used to determine the flow speed [19, 22]. It operates by transmitting and receiving ultrasonic sound waves from an emitting transducer and a receiving transducer [22]. As sound waves travel through air, the speed of the sound waves

will be affected by the wind velocity. Therefore by measuring the time difference taken for the sound waves to travel between the two transducers would be able to give the flow velocity as [22],

$$T = \frac{L}{c + v} \quad (2.6)$$

where T is the time taken, L is the distance between the transducers, c is the speed of sound and v is the air speed along the transducer axis.

One advantage of sonic anemometers is that they are able to obtain the speed, direction and angles of the wind velocity by arranging three pairs of transducers on three different axes. Also, due to the lack of moving parts, it has higher reliability. For this, it is widely used in the measurement of wind in wind turbines.

Figure 2.4 Sonic anemometer on wind turbine [28]

Measurements from sonic anemometers can be affected by small airflow distortions during calibration which would affect the measurements. Due to this problem, meticulous calibrations and corrections for such distortions have to be implemented. Weather conditions can influence the sonic anemometer's measurements. For example, heavy rains can reduce the data quality since the water droplets on the transducers can affect the time measured by the transducers. Dust particles also pose a problem for sonic anemometers when they adhere to the transducers and affect the accuracy of the measurements.

Since the transducers are usually made of electronic parts, they are electrically conductive and susceptible to lightning strikes. The holder of the transducer and receiver uses high strength stainless steel which poses similar problem.

2.1.4 Laser doppler anemometer

The laser doppler anemometer was first developed in the 1964 by Yeh and Cummins [29] from a complex laboratory technique in the past to a well-established measurement method used today.

The laser doppler anemometer is a type of measuring technique that uses the principle of the Doppler effect to measure fluid flow velocity [22]. Doppler effect is a phenomenon observed due to the motion of a wave producing source with respect to an observer. When the source approaches the observer, an up shift in frequency is detected in the signal. Similarly, when the source retreats from the observer, a down shift in frequency is detected. An example can be seen from the illustration in Figure 2.5 in which the observer will sense that the frequency is high when the car moves towards them and the opposite when the car moves away. The number of waves between the source and the observer remains constant as the distance between these object changes. This would mean that the rate at which the waves reach the observer changes.

Figure 2.5 Doppler effect [30]

The laser doppler anemometer can be operated using one or multiple lasers. The laser source is directed at the desired measuring point and a few laser pulses are fired. A photo detector is utilised to capture the light signals reflected or scattered by dust particles in the measuring fluid. The difference from the feedback signals from the photo detector and the original signals from the laser source generates the shift in frequency, which is the doppler effect. From there, the velocity of the dust particles can be computed.

Figure 2.6 Illustration of laser velocimetry [31]

There are many different types of configurations for the laser doppler anemometer system. The different configurations are due to the different placements of the laser source and the photo detectors. In some cases, inventors used multiple lasers to determine the three dimensional (3D) space flows.

A special type of laser doppler anemometer named Vindicator® [32] was developed by Catchthewind.inc to be mounted on wind turbines. Vindicator® makes use of a three laser beams system and is mounted on the nacelle of the wind turbine to measure wind velocity a few hundred metres in front of the wind turbine. It feeds wind information such as the wind speed and direction to the wind turbine controller which in turn utilise the data to optimally pitch the wind turbine blades. Research had shown that the Vindicator® was able to enhance the power efficiency of the wind turbine by 10% [32].

Recently, besides the Vindicator®, there are many various innovative inventions that integrate the laser Doppler anemometer system with the wind turbine to generate more efficient wind power systems. An example of such invention is a recent patent that describes the placing of the laser anemometer in the spinner [33]. This design could avoid the blockage due to the wind turbine blade rotation.

One of the main benefits in deploying the laser doppler anemometer is its capability of producing accurate wind information up to a few hundred metres away. By providing valuable wind data profile information to the wind turbine controller, it gives the controller ample time in pitching the blades to correct angle of attack and hence providing an optimum power production. In addition, the laser doppler anemometer is a non-intrusive measurement technique as it uses the laser system to measure wind speed and angle. Therefore the flow field would not be affected by the shape of the instrument.

Despite the laser doppler anemometer's ability to produce accurate wind velocities, it is unable to measure wind profile in close proximity. Some reports have claimed that producing wind velocities at short distances are possible albeit with a great reduction in the angle of view [34].

Laser doppler systems are relatively costly as compared to other wind velocity measuring systems as they require expensive laser and photo detector systems. The requirement for a transparent window for laser to shine through also creates the need for additional moving parts like the wiper system.

2.1.5 Fiber optics measuring techniques

Over the past twenty years there have been many developments on fiber optic based flow velocimeter. Flow velocimeter is important in many industries such as the petrochemical [35], medical and aeronautical industries [36, 37].

A few novel designs that use the concept of fiber based velocimeter has been developed recently [38, 39]. One such method is fiber based sensors that incorporate a hinge joint in their design. It is able to detect the flow velocity by the rotation of the hinge that causes a bend on the fiber which produces a reduction in signal [40]. Another flow meter uses the concept of a simple bluff body to pull the fiber resulting in the bending of the fiber was also demonstrated [37].

One of the cantilever type makes full use of a Michelson interferometer where by the interference caused by the light path of two beams resulted by the bending of the fiber [41]. The other cantilever uses an overlapping light spot to detect the displacement of the fiber. The amount of displacement displays the relation of the flow velocity with the bending curvature [39]. Another system uses the principle of vortex generated by the fluid flow to determine the flow rate which requires complicated polarization technique [42].

Fiber based velocimeter systems offer numerous advantages over other techniques such as Pitot tube, hot-wire anemometer, magnetic sensors etc. [42, 43]. As the fiber optics technique is encased, the sensing region is protected from dust and environmental factors. Fiber optics is the only electrical immune measuring technique compared to the other measuring techniques mentioned.

In addition, as it is a fiber based system, it is able to withstand temperatures up to 80⁰C, electromagnetic resistant and also quite robust in operating in harsh environment [39].

In addition, fiber optics has been used progressively to monitor the stress on the wing instead of measuring flow [13]. This technique is considered to be relatively new and its potential in wind turbine flow measurement application is worthwhile to investigate further.

2.1.6 Summary of Flow Measurement Techniques

Air flow measurement is a very important tool to optimise the power production in wind turbines. As technology advances, the methodology of measurement changes over time. Air flow measurement started off with mechanical anemometers with rotating parts and has evolved to pressure-based flow measuring devices which use the principle of Bernoulli's equation. The interest of ultrasound and the integrating sound changes with anemometry created the beginning of sonic anemometers. Similarly, the combination of laser and anemometry also gave rise to laser doppler anemometer. Lastly, fiber optics was deployed as another means of obtaining flow measurements.

Each measuring techniques has it pros and cons, depending on the type and requirement of the application. Cost is another factor that determines the type of deployment of the various measuring technique. The most expensive is the laser anemometer while the cheapest is the mechanical anemometer.

In this project, the placement of the measuring technique will be close to the tip of the wind turbine blade. The reason for this is that power production is largely determined nearer to the tip of the blade. In other words, the tip is the most effective section of the turbine that is responsible for harvesting most of the wind energy. This is due to the moment effect, as the work done come from the multiplication of the force and distance, hence higher work done (moment) is at the tip of the blade.

With that, placing an anemometry device at the wind tip provides the most accurate location for flow measurement. Very often, wind turbine anemometer is mounted at high altitude for accurate data. Placing the anemometry technique at such a high altitude poses lightning attraction threat especially for conductive materials. In addition, high altitudes also pose difficulty for servicing and maintenance of the equipment. Hence the measurement technique has to ensure high reliability standards with low maintenance requirement. The Table 2.1 below provides a summary of the sensing devices mentioned in the literature review against the design requirements of this project.

Figure 2.7 Illustration of lightning striking a wind turbine[44]

Table 2.1 Overview of the flow measuring devices

*5 being the most important or high performance, 1 being the least performance

Device Design Requirements	Relative Important	Mechanical Anemometer	Pitot Static Tube	Sonic Anemometer	Laser Doppler Anemometer	Fiber Optics Velocimeter
Lightning Attraction Issues	5	1	1	1	1	4
Immune to dust	4	2	1	2	2	4
High reliability (Uncertainty Factors)	5	3 [45]	2 [45]	3 [45]	3 [45]	3 (Approximated)
Accuracy	4	1 $\pm 1\%$ [45]	2 $\pm 0.5\%$ [45]	2 $\pm 0.5\%$ [45]	4 $\pm 0.2\%$ [45]	2 (Approximated)
Cost	2	4 \$300 to 1800 [46]	5 \$300 to \$500 [47]	2 2000 to \$2,800 [48]	1 >>>\$5,000	3 $\approx$ \$1,000
Total Score	100	40	37	40	46	69

Lightning attraction issues basically describes how the instrument avoids being affected by lightning strikes, as high altitudes increase the chances of lightning strikes. Instruments like the mechanical anemometer, the sonic anemometer, pitot static tube and laser doppler anemometer requires the use of electronic circuits close to the measurement location and hence increases the probability of lightning attraction as the electronic circuits conduct electricity which would naturally attract the lightning currents. However in the case of the fiber optic sensor, it is able to extend the measurement (fiber) further away from the measuring locations before deploying its electronics and therefore the probability of attracting lightning currents is greatly reduced.

“Immune to dust” describes how well the instruments operate in dusty environment. Mechanical anemometer performs quite robust in dusty environment, the only issue is that there are gaps due to the rotating mechanism and dust would get entrapped in it causing some potential issues. Pitot static tube has the worst performance in the dusty environment as it is highly dependent on some orifice in order to detect the differential pressure. These small

orifices are prone to clogging and would greatly affect the reliability of the pitot static tube. Sonic anemometer performs relatively well in the dusty environment as the transducer and the receiver is protected from the environment by a casing. However dust might adhere to the surface of the receiver and affect the accuracy of the readings. As for the laser doppler anemometer, it requires a clear window for the laser to pass through and to reflect back into the sensor. Dust would adhere to the operating window and affect the reflected laser beam causing an inaccurate data collection. Despite all the issues, fiber optic sensors are the least affected by dust as the light paths are internal and the fiber are encased by a protective cladding layer.

The score chart for the uncertainty factors is presented in Table 2.1 whereby referenced from Table 2.2. Table 2.2 displays a summary of the uncertainty factors for the Laser doppler Anemometer, Ultrasonic anemometer and the Pitot Static Tube.

Table 2.2 Uncertainty factors for various types of anemometers[45]

Anemometer	Uncertainty factors
LDA	Beam crossing angle, Doppler frequency, fringe divergence, wavelength
Ultrasonic	Sensor distance, sound speed, time measurement, ...
Pitot tube	Air density, differential pressure, expansibility, sensor alignment
Thermal	Curve fitting uncertainty, temperature, voltage
Rotational	Sensor alignment, radial location of rotating parts, rotating speed

After the comparison with the all the values in the design chart, it is clear that fiber optics sensors have the edge over the other measuring techniques. However, the technology is not as mature as the other techniques. Therefore, this report aims to develop the fiber sensor technology further and develop it into novel applications.

2.2 Active control techniques

2.2.1 Introduction to active control techniques

The wind turbine uses various types of control techniques to constantly direct the wind turbine to wind direction in order to obtain optimum power production. There are two main types of techniques, passive control or active control.

Passive control is a technique that does not require external input or force to steer the wind turbine to wind direction. A typical example of a passive control technique can be seen in the addition of the boom to the back of wind turbine. Another example would be the downwind

wind turbines. Both of these techniques eliminates the need for additional forces to steer the wind turbine as the aerodynamic forces generated by the boom due to differential pressure will automatically steer the wind turbine in the yaw direction.

Figure 2.8 An old wind mill with a boon [49]

Active control techniques require an input steering force for the system. This force yaws the wind turbine into the direction of the wind for maximum power production. Besides, there are open loop control and closed loop control [2, 50] systems. Open loop control is a control technique where the actuating motion is activated upon requested and there is no control of the actuating motion. A closed loop system operates using a feedback system where information of the actuating motion is constantly sent back to the control system to improve reliability and obtain optimum controls of the system. The feedback of the system is usually through a sensing or measuring instrument. Therefore a closed loop system will be able to obtain the optimum angle of attack or profile to achieve the maximum power output as compared to an open loop system. In this report, the focus is placed on the active close loop control system.

There are several control techniques that was mentioned, such techniques used are the micro tabs, micro flaps, plasma actuators and shape changing aerofoil. There is also high emphasis on micro tabs as it is relatively small in size but proven to be very effective [51]. However, all these techniques require reliable sensing techniques to operate smoothly and effectively.

2.2.2 Angle of attack (AOA)

In addition to the flow velocity, essential information that needs to be actively fed to the turbine control system is the angle of attack. The computation of the angle of attack from measuring equipment will contribute to the pitching of the wind turbine blades for optimal power production, for example anemometers in at the nacelle of the wind turbine can input general wind direction and velocity into the computer which in turns control the pitching of the wind turbine blades.

Some reports have shown the relationship between the angle of attack and wind velocity: it was found that the optimum angles of attack for untwisted blade wind turbine are 4.12° , 5.28° , 6.66° , 8.76° for wind speeds of 7.2 m/s , 8.0 m/s , 9.0 m/s , 10.5 m/s respectively [52]. This clearly indicates that there is an optimum angle of attack at each respective wind speed. Therefore, there is a need to know the flow speed and their corresponding angles of attack [52].

There are various methods in obtaining the angles of attack (AOA) [53]. One method of obtaining the AOA is through the monitoring of the load distribution on the wind turbine blades. Wen *et al* [45] mentioned two techniques that employ the biot-savart integral in his formulation to determine the AOA. The first is based on known force distribution while the second one is based on known pressure distribution which is obtained from numerical calculations. Besides Wen *et al*, there are other reports on the estimation of the AOA from blade pressure measurement using axial [54] and yawed condition [55].

2.3 Fluid flow over an airfoil

This section provides a fundamental overview of the fluid dynamics over an airfoil. Fluid medium such as air or water flows over a particular surface, lift and drag forces will act on the surface due to the pressure differences. The scope of this project is focused on fluid flow over the wind turbine blades. Airfoil profile NACA 63415 is selected as the design airfoil since many general wind turbine blades follow this profile. In addition, there were many validated wind tunnel measurements [7] conducted on this profile. Hence, to facilitate the comparison of fluid dynamic wind data, the NACA 63415 was used.

2.3.1 Introduction to fluid dynamics

The fundamentals of fluid mechanics including the Navier-Stokes equations are described in Appendix A for better understanding. Navier-Stokes equations can be further simplified to obtain the Bernoulli's equation which was mentioned in the earlier section 2.1.2. The following two assumptions are made in the derivation. Firstly, the flow has to be incompressible, where the density does not change along the streamline. Secondly, the flow

has to be inviscid, where the viscous forces are small in comparison to the inertia forces. In the area of wind turbine, the rate of flow ranges from 0 m/s to 20 m/s. At this range, it is categorized as a subsonic flow since the flow rate is well below 330 m/s, the speed of sound. The classification of the flow in the subsonic region allows the air density to be considered constant regardless of the air pressure.

Fluid flow is classified into three different types of flow, typically laminar flow, transition flow and turbulent flow. In 1880s, the experimental work by Osborne Reynolds led to development of Reynolds number.

The Reynolds number (Re) is a dimensionless number that gives the relationships between the inertial force and the viscous force and it quantifies the relative importance between the two type of forces [56]: a function of fluids density, viscosity, velocity and a characteristic length or characteristic dimension.

$$Re = \frac{\rho v L}{\mu} = \frac{v L}{\vartheta} \quad (2.7)$$

where, v is the mean velocity of the object relative to the fluid (SI units: m/s), L is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m), μ is the dynamic viscosity of the fluid (Pas or Ns/m² or kg/(ms)), ϑ is the kinematic viscosity ($\vartheta = \mu/\rho$) (m²/s), ρ is the density of the fluid (kg/m³).

It is to be noted that the Navier-Stokes equations that were presented in Appendix A could be simplified into the Bernoulli's Equation 2.2 based on incompressible and inviscid flow condition. From the Bernoulli's equation, it can be seen that the pressure changes with respect to the flow velocity as well as the position of point of reference. In the application of wind turbine, Bernoulli's principle can be used to calculate the lift force on an aerofoil if the shape is known.

For example, in an aerofoil, if the air which flows past the top surface of a blade is moving faster than the air which flows past the bottom surface, then Bernoulli's principle implies that the pressure on the surfaces of the wing will be lower above than below. This pressure difference results in an upwards force which is also known as the lift force. Whenever the distribution of pressure or flow velocity past the top and bottom surfaces of a blade is known,

the lift forces can be calculated to a good approximation using Bernoulli's equation. The illustration below shows the distribution of pressure and flow when the air travels across the blade.

Figure 2.9 Pressure differences on an aerofoil [57]

2.3.2 Streamline

In the analysis of fluid flow over an airfoil, streamlines are used to depict the motion of fluid path line. In the formation of streamlines, streamlines follow a couple of rules [56].

- 1) Mainly used for 2-Dimension flow
- 2) The point where the velocity of the flow is zero is called the stagnation point.
- 3) Streamlines can only intersect at the stagnation point.
- 4) The total volumes between two streamlines are the same.
- 5) The velocity is tangential to the streamline at every point.

Figure 2.10 Streamline of the aerofoil

Figure 2.10, shows that point 1 and point 2 lies on the same stream line, in this cause the amount of energy is the same for the two points. As mentioned in Chapter 1, the Bernoulli's principle is derived from the principle of conservation of energy. It is applied to streamlines whereby the sum of all forms of mechanical energy in a fluid is the same at any point along

that streamline. This means that the sum of kinetic energy and potential energy remain constant. Thus an increase in the speed of the fluid occurs proportionately with an increase in both its dynamic pressure and kinetic energy, and a decrease in its static pressure and potential energy.

Figure 2.11 Flow fields or streamlines under a) low angle of attack b) high angle of attack c) stalled flow[58]

Figure 2.11 illustrates the 3 different flow regions, namely laminar, transition and turbulent flow, though transition flow is hardly noticed in the Figure 2.11. In the low angle of attack, the flow is considered to be laminar flow. As one can observe that the streamline which is similar to the Figure 2.11, the lines do not cross each other. However as the angle of attack increases where it becomes the stalled flow, turbulence start to occur at the trailing edge of the profile.

2.3.3 Surface Pressure variation

Before going into details, the some definitions are made so as to obtain better clarity.

- *Leading edge* is usually the front of the aerofoil which has the maximum curvature.
- *Trailing edge* is usually the rear of the aerofoil which has the minimum curvature and it usually ends up as a point.

Figure 2.12 Definitions of an aerofoil [59]

In order to provide sufficient lift, most aerofoils are designed to be curvy at the upper surface. This curvature at the upper surface will accelerate the flow at that area increasing the velocity at the upper surface as compared to the lower side. Applying the Bernoulli's principle, the increase in velocity would cause a drop in pressure. With a pressure gradient drop at the upper surface as compared to the lower surface, lift force is thus generated.

To sum up, the lift force is produced due to the differential pressure between the suction surface and the pressure surface. Overall, the lift on an aerofoil is primarily the result of its angle of attack and shape.

Figure 2.13 Surface Pressure variation of an aerofoil [60]

Engineers often use experimental data or theoretical solutions of a known flow conditions to gain knowledge of the flow field of another flow condition. It is useful to obtain correlations

in terms of dimensionless coefficients which depend only upon the configuration geometry and upon the angle of attack. The pressure coefficient is one such coefficient [60].

$$C_p = \frac{P - P_\infty}{\frac{1}{2} \rho_\infty U_\infty^2} \quad (2.8)$$

where C_p is the coefficient of pressure, P is the pressure, P_∞ is the ambient pressure, U_∞ is the ambient velocity and ρ_∞ is the ambient density. The coefficient of pressure, C_p can be plotted to illustrate the surface pressure variation of a blade profile.

In summary, the mechanics of flow over a surface are briefly introduced in this section. The detailed derivations of the equations are not included in this report since the scope of this project does not require the coverage of such details. The focus of this project is to propose a novel sensing method for wind turbines. The basic fluid mechanics that were discussed and covered in Appendix A will be sufficient for the development of the flow measurement technique. Some important point to take note that the assumptions used in application of the flow field, with the first assumption being that the fluid is a continuum. Next, the density of the fluid remains constant and hence incompressible flow. Lastly, the viscous effect of the fluid is defined to be small resulting in the assumption of inviscid flow where Reynolds number is small. With all the assumptions and the conservations laws, the Bernoulli's equation is used to define the flow along the streamlines. Pressure coefficient is also introduced to give the reader a heads up on the terms used.

Chapter 3

Fiber Optic Flow Measurement Device

The first stage of this project included the production of a prototype fiber sensor which was mounted on a plate for measurement and validations. Flaps were attached onto the fiber sensor to enhance the measuring sensitivity and range. The next stage of application comes after the validation of this prototype. Two novel applications of this sensor were developed, namely as an angle of attack sensor and a stall detector.

3.1 Fiber Flow Measurement System

A sensor prototype with a mini bending fiber sensor that is able to measure the air without any external support was developed. The fiber is able to support itself on its own stiffness. With no requirement of an external support and hence no complicated equipment, vast benefits like cost effectiveness and design simplicity are achieved. The fiber would also consume less power as compared to other flow measurement systems.

3.1.1 Operating Principle

The principle behind the fiber system comes from the observation of hair on the human skin relating to how it is able to “sense” wind blowing across it. A simple way to explain the mechanism of the fiber sensor is to relate it to a cantilever beam extended out into the free stream velocity without any additional tools attached. As wind blows across the cantilever, it creates a drag force which will bend the fiber. Applying the formula of the fiber optic bending motion, the velocity of the flow can thus be derived from the deflection.

An expression for drag force F_d is given by:

$$F_d = \frac{1}{2} c_d \rho A u^2 \quad (3.1)$$

where C_d is the drag coefficient and is assumed to be 1 [61, 62] because it is a thin cable that stands straight perpendicular to the direction of the flow, ρ is air density, A is the frontal surface area of the fiber in direct contact to the air flow and u is the mean flow velocity, see Figure 3.1.

Figure 3.1 Deflection of the fiber under drag force

The amount of total drag force is calculated based on the frontal area of the fiber in contact with the fluid flow according to Equation 3.1. Due to non-slip boundary condition at the wall surface, there is the presence of a boundary layer. There will be skewed distribution load as shown in Figure 3.1, where a large force is acting nearer to the tip of the fiber. Hence for a simplified calculation, the total drag force is approximated as a concentrated load at the end of the fiber (cantilever tip).

The angle of deflection θ , in accordance to the Euler infinitesimal beam deflection theory for a single point load is given by:

$$\theta = \frac{F_d l^2}{2(EI)_{eq}} \quad (3.2)$$

where l is the length of the fiber; $(EI)_{eq}$ the effective flexural rigidity of the optical fiber core and outer cladding system; E the Young's modulus of the fiber material and I the second moment of area. E is obtained from the fiber material property and it varies according to the fabrication of the fiber, which is approximated at 1 GPa [63]. A separate literature source on strain sensor measures the Young's modulus of the fiber to be between 0.248 and 3.367 GPa [64]. Based on these references and for simplicity, the Young's modulus, E value of the fiber for this project is assumed to be 1 GPa. The product of Young's modulus and second moment of area gives the bending modulus. The overall bending modulus, Bending Modulus Equivalent $(EI)_{eq}$ is used in Equation 3.2 as the fiber is made up of two different materials, an inner circular core of light transmitting medium *polymethylmethacrylate* (PMMA) and an outer case made up of epoxy. $(EI)_{eq}$ is calculated by adding the Bending Modulus of the PMMA inner core with the Bending modulus of the Epoxy. The bending modulus is

calculated by multiplying the Young's modulus, E , with the second moment of Area, I , as shown in Figure 3.2.

Combining Equations 3.1 and 3.2, the angle of deflection can be represented as

$$\theta = \frac{(c_d \rho A u^2) l^2}{2(EI)_{eq}} \quad (3.3)$$

The fiber system that was used utilises step-like grooves, which were created on the fiber's cladding to promote localized power lost through bending, so that the power loss is directly linked to the bending at groove region, as shown in Figure 3.2 [65].

Figure 3.2 Cross section of the fiber and the grooves created on the fiber

Figure 3.3 The fiber instrument measured calibration

The fiber optical instrument used in this project was based on [65]. Figure 3.3 displays the percentage drop in transmission against the bending angles from 0 to 80 degrees. The fiber

was placed on a protractor to determine the amount of deflection and using mechanical fixtures, it was bent to specific angles and the output voltages were recorded. A total of three (3) sets of readings were recorded and the readings were illustrated in Figure 3.3.

The fiber optical instrument will result in a drop in voltage when the fiber is bent.

$$V_{out} = V_0 - V_m(\theta) \quad (3.4)$$

where V_{out} is the voltage output, V_0 is the initial voltage where there is no bending of the fiber, $V_m(\theta)$ is the measured calibration of the instrument, it is the inherent instrumentation property that changes the output voltage in accordance to the bending angle. $V_m(\theta)$ is obtained through a series of tests where the fiber is placed on a particular angle scale and the fiber is bent from 0° to 80° . At each interval of 10° , the voltage output is obtained and plotted. Figure 3.3 demonstrates the voltage output against the change in bend angles.

Combining with Equations 3.3 and 3.4,

$$V_{out} = V_0 - V_m \left(\frac{(c_d \rho A u^2) l^2}{2(EI)_{eq}} \right) \quad (3.5)$$

Equation 3.5 provides a relationship between the voltage drop and the flow speed. The variables affecting the deflection are the fiber surface area, the length of the fiber and the flow velocity. Fiber length is fixed at l , due to the fabrication limitations of the current fiber bending system. The surface area effect on voltage would be investigated in this setup by employing a flap on the tip of the fiber and is discussed further.

3.1.2 Finite Strain Analysis of the fiber

In the analysis in the previous section, the Euler beam theory is deemed to be accurate only for small deflections and could not be applied when in situations where the beam undergoes large deflections. As a result, the large deflection beam theory was applied to provide a more accurate analysis of the beam.

The large deflection theory is based on a uniform-section of circular beam of linear elastic fiber [69] as shown in Figure 3.4. The equation representing the large deflection theory is shown in Equation 3.6.

$$EI \frac{d\phi}{dS_c} = M \quad (3.6)$$

where M is the bending moment, $\frac{di}{dS_c}$ is the curvature and I is the second moment of area. The assumptions made is a point concentrated load similar to Equation 3.2 for comparison with the Euler Beam theory.

Differentiating the Equation 3.6 with respect to S_c , refer to Figure 3.7, leads to:

$$EI \frac{d^2\phi}{dS_c^2} = \frac{dM}{dS_c} \quad (3.7)$$

where the bending moment M at a point A with Cartesian Coordinates is given by:

$$M(S_c) = F(l - \delta_x - x) \quad (3.8)$$

By differentiating the equation with respect to S_c , $\cos di \frac{dx}{dS_c}$ and substitute into the Equation 3.7, the non-linear differential equilibrium equation is obtained:-

$$EI \frac{d^2\phi}{dS_c^2} + F \cos n \quad (3.9)$$

Multiply the Equation 3.9 by $\frac{d}{dS_c}$:

$$EI \frac{dI}{dS_c} \left(\frac{d^2\phi}{dS_c^2} \right) + F \cos i \left(\frac{dF}{dS_c} \right) = 0 \quad (3.10)$$

Factorise the above equation gives

$$\frac{d}{dS_c} \left[\frac{1}{2} EI \left(\frac{dI}{dS_c} \right)^2 + F \sin \right] = 0 \quad (3.11)$$

The above equation should be solved subjected to the boundary conditions free end of the beam, $\phi(l) = \phi_o$ and $\left(\frac{da}{dS_c} \right)_{S_c=l} = 0$;

$$\left(\frac{d\phi}{dS_c} \right)^2 = \frac{2F}{EI} (\sin \phi_o - \sin \phi) \quad (3.12)$$

Hence by solving the equation for arc length S_c :

$$S_c = \sqrt{\frac{EI}{2F}} \int_0^\phi \frac{1}{\sqrt{\sin \phi_o - \sin \phi}} di \quad (3.13)$$

The total length L can be written as

$$L = \sqrt{\frac{EI}{2F}} \int_0^{\phi_o} \frac{1}{\sqrt{\sin \phi_o - \sin \phi}} d\phi \quad (3.14)$$

Rearranging,

$$\int_0^{\phi_o} \frac{1}{\sqrt{\sin \phi_o - \sin \phi}} d\phi - \left(\frac{2FL^2}{EI} \right)^{1/2} = 0 \quad (3.15)$$

Once the large deflection theory is established to determine the motion of the fiber, it can be utilised to analyse the bending motion of the fiber.

$$V_{out} = V_0 - V_m(\phi_o) \quad (3.16)$$

Similar to Equation 3.4, where V_{out} is the voltage output, V_0 is the initial voltage where there is no bending of the fiber, $V_m(\phi_o)$ is the same measured calibration of the instrument as per Equation 3.5, however it is dependent on ϕ_o which is the calculated angle of deflection per Equation 3.16 [65] .

Based on the drag force equation as presented in Equation 3.1, there is a requirement for the instantaneous velocity at the fiber location to be known so that the velocity can be inserted in to the equation. This instantaneous velocity is calculated by performing CFD simulations.

Figure 3.4 Schematic illustration of the finite strain analysis

3.2 Initial Experimental Setup

An initial experiment setup was created on the flat test bed to determine the feasibility of using fiber optic sensor as a flow sensor. The steps mentioned below describe the procedures and the equipment setup required to perform the test.

3.2.1 Initial Experimental Setup

An experimental apparatus (prototype) was set up to determine the flow velocity sensing. It was conducted in a LW-3890 wind tunnel. Experimental flow velocity between 0 to 3 *m/s* was not considered as the wind tunnel could only operate accurately in the region of more than 3 *m/s*. The test was conducted at wind speeds of 3 to 15 *m/s*.

3.2.1.1 Optical Fiber

The fiber is a single mode fiber with a centre core made of *polymethylmethacrylate (PMMA)* encased in an epoxy adhesive material for enhanced endurance and protection. Step-like grooves were created only on the cladding to enable the fiber to have a higher reduction in light transmission when bent at these regions [65]. When the fiber is bent, it was found that only the region with these grooves would cause a significant reduction of light intensity as compared to the rest of the fiber. Therefore, it was concluded that other parts of the bent fiber would not have a significant effect on the output voltage measurement and hence the bending of the fiber at other locations would not affect the results [65].

Figure 3.5 shows the working principle of this sensor system. It starts with a light emitting diode transmitting light into the fiber and the intensity of the light is reflected by a mirror to the photo detector, which will be able to determine the amount of light loss. The signal is next amplified and fed into a NI-USB 6221 data acquisition system (DAS) via an amplifier to produce an output signal in voltage.

Figure 3.5 Schematic of the optical fiber based flow sensing system (mm)

3.2.1.2 Optical Fiber Holder

To hold the optical fiber into the wind tunnel for testing, a fixture is needed to hold the fiber in place. A flat piece of aluminium plate was used to fabricate the fixture with a hole to insert the fiber. Adhesive was applied at the hole to secure the fiber to the plate, as shown in Figure 3.5. The section of the step grooves were carefully positioned such that they laid at the fixed support on the flat plate. After the fiber was inserted, the rest of components were placed together with the metal piece for mounting in the wind tunnel. Dimensions of the optical fiber with the holder plate are depicted in Figure 3.6.

Figure 3.6 Dimensions of the fiber holder plate setup (mm)

3.2.2 Fiber Optics Sensor Flap Size investigation

To alter the sensitivity in the fiber cantilever system, groove etching [43] may be used, however, this method is costly due to the intricate etching techniques involved. The simple and inexpensive technique of attaching a flap to the fiber free end in a bid to enhance the sensitivity of the flow measurement was utilised in this project.

Based on Equation 3.1, adding a flap increases the contact area A which amplifies the drag force. This amplification of drag force affects the sensitivity of the measurement; an investigation was conducted to determine the possibility of such implementation.

A piece of flap was added to the tip of the fiber to increase the surface area since it was supported by Equation 3.1 that the drag force can be increased by increasing the area. Increasing the area however, may cause interruption to the laminar flow flowing across producing eddies and causing the flow to be more turbulent.

To study the effect of surface area on the sensitivity, an adhesive tape was used as the flap. Two different areas were accurately cut to size and attached to the tip of fiber. The thickness of the tape was approximately 0.1 mm and was assumed to have negligible effects on the stiffness of the fiber at 1 mm thickness. The two flaps differed only in widths with the other dimensions remaining constant for a direct comparison. The different flap sizes used are listed in Table 3.1

Table 3.1 Different flap sizes attached to the optical fiber

Flap	a) No Flap	b) Small Flap	c) Big Flap

Area	46 mm^2	101 mm^2	156 mm^2

3.3 Application of the Fiber optic sensor on NACA63415 airfoil

After validation of the one dimensional optic fiber flow sensor mentioned in Sections 3.1 and 3.2, two different novel applications were developed. The two techniques mentioned in this report have been filed and are pending patent application, highlighting its novelty in the application area of the wind turbine flow measurement.

3.3.1 Experimental setup

Wind tunnel experiments for the flow measurement are designed with the aid of computational fluid dynamic (CFD) simulations carried out using Xfoil software, developed by Mark Drela from Massachusetts Institute of Technology [66] to analyse subsonic airflow pattern, drag and lift coefficients on a two-dimensional (2D) profiles.

Experiments were conducted using the NACA 63415 airfoil, a widely studied airfoil [7, 67] with general wind turbine blade profile. Styrofoam boards were cut to the NACA 63415 profile using a hot wire cutter and joined together using a two-part araldite adhesive. Two aluminium rods were inserted into the blade profile to be for actuating the aerofoil to the desired angle of attack (AOA). One sided smooth black adhesive tape was wrapped over the brittle surface of the styrofoam to provide additional stiffness/support and to decrease surface roughness. After the sections were combined, the fiber optic sensor was installed into the air foil extruding out of the surface as shown in Figure 3.7.

Figure 3.7 Positioning of the fiber at 65% chord length

Two aluminium rods are mounted to the base plate inside the wind tunnel. The base plate can be rotated using a lever operable outside of the wind tunnel. The dimensions of the wind tunnel test section are 720mm (W) x 780mm (H) x 1000 mm (L) [68].

As the length of the fiber is relatively long, the air foil was required to be large and yet small enough to avoid the choking effect of the wind tunnel test. Similar to the venturi effect, the choking effect is where the mass flow rate will not increase given a reduction in the downstream pressure. The final optimum profile was built to 640 mm for the chord and with a span of 600 mm.

3.3.2 AOA Sensor

Xfoil was used to generate coefficient of pressure (C_p) profiles at Reynolds number of 5×10^6 . Figure 3.8 shows the change in C_p values at the various chord lengths as a function of various AOAs. The plotted C_p values can be used to determine the actual pressure that is acting on the surface of the profile.

Figure 3.8 C_p values of the NACA 63415 from AOA 0° to AOA 12° at $Re = 5 \times 10^6$

From Figure 3.8, it is observed that there is a correlation between the AOA and C_p values. The top portion of the graph refers to the top surface and the bottom portion of the graph refers to the bottom surface.

It was noted that when there is a negative relation between AOA and C_p values of the top surface, this trend could be utilised to develop the sensor. As such, by placing a sensor at the location which allows it to detect the pressure or velocity changes, the AOA values could then be determined.

3.3.3 Computational Fluid Dynamics (CFD) simulation

A NACA 63415 model was created using Solidworks®. The simulated model geometry is similar to the one created for the wind tunnel test. However, the edges of the model were rounded off to reduce meshing errors. A semi circle with a rectangular domain boundary was created around the model for the fluid domain. The height of the domain is 10 times the chord length and the length of the domain is 20 times the chord from the aerofoil, see Figure 3.9, the reason for such a large domain is to sufficiently avoid the side wall effects, i.e. boundary layer effects from affecting the simulated results. The width of the domain is kept to just 10 mm. This is kept small to reduce the number of meshing, as symmetrical boundary conditions will be set, the width of the profile does not affect the simulation.

The meshing was performed using the “Automatic Mapping” option offered by Ansys® commercial finite element software meshing module. The mesh was made up of close to 570000 tetragonal mesh elements (as tetragonal elements offer a more accurate result compared to prism elements). In the analysis, Reynolds Averaged Navier-Stokes (RANS) model was selected and the SIMEPLEC was chosen as the main solver for the simulation to compute the solutions for the 4 equations namely, the energy equation and the momentum equation in the X, Y and Z axes. The analysis was conducted in a steady state condition similar to the experiment setup where the fiber was bending in the flow field for a relatively long period of time.

Figure 3.9 Finite element mesh around the NACA 63415

Figure 3.10 Close-up view of the mesh

The model and the analysis were first tested to determine the accuracy of the results by comparing the simulated results with known experimental data[67]; the results can be seen in Appendix B.

The simulated results from the CFD analysis conducted using Fluent shows that there is a slight deviation of less than 10% as compared to the experimental results from Bak *et al*, who had performed similar analysis on the NACA 63415 air foil [67] as shown in Appendix B. A number of reasons could be attributed to the deviation, one of which being the meshing method and the rounding-off of edges at the trailing edge. Another reason is due to the analytical assumptions that are embedded within the simplified force models and equations

used in this report. As the difference between the two results is not significant, the simulation could be implemented in this project.

The wind tunnel parameters were next input into Ansys work bench and calculated for 15000 and 10000 iterations. Results from the 15000 iterations were compared against that of 10000 iterations and it was determined that there was no difference between the two results. In order to reduce the amount of simulation time, the number of iterations was kept at 10000. The results of the simulated velocity were taken only when the residuals of the continuity equation and the X, Y and Z momentum drops below 10^{-6} . The simulation would run for values of angles of attack, ranging from -16° to 16° , similar to the actual experiment that would be conducted. The simulation would enable the generation of the instantaneous velocity of the fiber, which can be used for calculation to determine the force acting on the fiber.

3.3.4 Stall detector

It has been recorded, by various experiments and simulations that airfoil NACA 63415 starts to stall from 14° angle of attack. Figure 2.11 below shows the air flow characteristics during the low AOA, high AOA and stalled airfoil [7, 67].

From the analysis that was presented earlier with regards to the flow separation, Xfoil was used to verify the separation and position of the fiber to be placed.

Figure 3.11 Xfoil simulation NACA 63415 airfoil, $Re = 5 \times 10^6$ at 14° AOA

Figure 3.11 shows the simulated NACA 63415 airfoil at under Reynolds number of 5×10^6 at 14° angle of attack using Xfoil. The simulation shows that from 0% to 50% chord, the flow is closely attached to the air foil. After 60%, flow separation occurs. Therefore the position to place the fiber is between 60% to 70% chord length, see Figure 2.11c and Figure 3.11.

Figure 3.12 Completed blade profile for testing with optical sensor

Chapter 4

Results and Discussion

Previous work on optical fiber measurements consists of simpler designs which measured low wind velocities of up to 3 m/s [43]. Although the design proposed in this report is similar in principle to the work done by Schmitt *et al.* [43] and Rong *et al.* [37], it has the advantage over the other measurement technique in its ability to measure air flow velocities of up to 15 m/s with certain linearity in the measured region. Also, the suggested design does not require any complicated interferometry equipment or any high powered laser systems. Instead, the fiber functions using low power light emitting diode and the change in the curvature results in a reduction in the light intensity returning to receiver. The power requirement of this method is small compared to other systems. There is a correlation between the reduction in the voltage due to the bending of the fiber and the flow velocity. Therefore, it can serve as a reliable flow sensor for a range of flow velocities between 0 m/s and 14 m/s . The fiber is 46 mm in length and the overall width (as it is a rectangular shape) of the fiber with the encasement is 1 mm which is small in relation to the magnitude of the application, which in this case would be the span of the diameter of a wind turbine blade which is 80 metres for the V164 Vestas 8MW wind turbine [17]. The small size of the fiber would mean that there would be minimal disturbance to the flow field and accurate results can be obtained.

4.1 Fiber optics flow measurement

The experiment was conducted on the fiber with flaps from flow velocities of 0 to 15 m/s . The raw voltage output, recorded using the data acquisition system for a typical applied flow rate, is shown in Figure 4.1. The setup has a data collection frequency of 1,000 data points per second. In this setup, voltage is captured for a period of 100 seconds.

Figure 4.1 Voltage output data for flowrate of 10 m/s

Figure 4.1 shows the voltage output in real time monitoring. Data fluctuations were observed due to environmental factors and a slight damping from the fiber itself. Hence there is a need to plot the normalized or the average values and the standard deviation plot to minimise the impact of analysis of the results due to the noise in data. This was plotted in Figure 4.2 which demonstrates the standard deviation measurements at different flow rates. The plot is based on the average values and the bars display the maxima and the minima values of the data. The start of the experiment begins at 5 volts where there is no flow rate to cause any voltage drop as there is no bending of the fiber. As the flow rate increases, the fiber bends, resulting in the voltage drop as seen in Figure 4.2. For comparison, the theoretical voltage drop with external air flow given by Equation 3.5 and Equation 3.16 is shown and represented by the red and blue line respectively in Figure 4.2.

Figure 4.2 Experiment data of no flap and theoretical results

Observation from Figure 4.2 reveals that there is an approximately 5% deviation between theoretically calculated voltage values and the experimental measurements after 10 m/s and the deviation increases as the flow rate increases. The reasons for this deviation are the following:

The bending model of the fiber does not take into account of the change in the fluid flow due to the bending of the fiber and as the fiber bends, the coefficient of drag changes due to the change in fiber orientation. Despite the difference between the theoretical and the experimental results, it is able to give clear values of the different flow rate based on the voltage drop and hence can be used effectively as a flow rate velocimeter at the linear region from 0 m/s to 14 m/s with a sensitivity of -0.0922Vs/m.

The theoretical results allow a comparison of the Euler beam theory and the large deflection theory. At a lower flow velocity of 7m/s, the bending angle of the fiber is less than 10° and similar results from the Euler beam theory and large deflection theory were observed. The results from these two theories at this low deflection were also closely related to the experimental measurements. However, as the flow velocity increases, the fiber undergoes a larger deflection and results in Figure 4.2 show that the Euler beam theory will give a larger and more inaccurate deflection result while the large deflection theory had a better affinity with the experimental measurements.

4.2 Effect of Flap on the sensitivity

With the addition of the flap, the voltage output against the flow rates are shown in Figure 4.3a and 4.3b. It was observed that with the presence of the flaps, the voltage saturates to a constant value at a lower flow rate. The range of flow detection ability was greatly reduced. The small flap produced a linear region from 4 m/s to 8 m/s with a sensitivity of -0.195 Vs/m while the big flap produced a linear region from 3 m/s to 5 m/s with a sensitivity of -0.27 Vs/m. The increase of the area of the flap would bring about an increase in the sensitivity but would cause a decrease in the range of linear region.

Figure 4.3 Different flap Voltage output with a) theoretical analysis b) linear equation

From Equation 3.1, the increase in the contact area A would result in an increase in the drag force and thus affecting the final Equation 3.5 and Equation 3.16. Increasing the contact Area A has brought about the increase of the voltage results. This is validated by the trend observed in the experimental measurements where the reduction of range would bring about an increase in sensitivity.

Figure 4.4 Photographs of optical fibers in the wind tunnel: a) No flap, 0 m/s; b) No flap, 15 m/s; c) Small flap, 15 m/s and d) Big flap 15 m/s

Figure 4.4 shows the deflection profile of the optical fiber at 0 and 15 m/s with different flap sizes. The inherent material property of the fiber allows the fiber to be upright without any external support when there is no fluid flow. This is why it can be ascertained that there was no bending of the fiber and hence zero voltage drop at 0 m/s from Figure 4.4a. At a flow rate of 15 m/s, the bending of fiber without flap appears to have more room for bending. For the fiber with the small flap, it can be observed that there is a significant change in deflection in the 0 m/s to 10 m/s range. However, beyond the velocity of 10 m/s, the difference in deflection is hardly noticeable. In the case of the big flap, the change in deflection is significant up to 6 m/s.

4.3 Angle of attack sensor

The angle of attack sensor was analysed by both theoretical (simulation: using Ansys® Fluent) and experimental methods. The flow chart in Figure 4.5 describes the steps to taken to perform the theoretical analysis.

Figure 4.5 Flow chart of the theoretical analysis

In order to perform the theoretical analysis, the following steps are taken:

- Instantaneous velocity at the fiber location must be determined so that the values can be implemented into the drag force equation.
- From the drag force formulation, the amount of force acting on the fiber can thus be determined.
- Based on the amount of force acting on the fiber, the amount of deflection can be derived by implementing the large deflection theory, as elaborated in Section 3.3.2 and given by the Equation 3.6 to 3.16 where the force is based on the drag force calculation in Equation 3.1.
- The large deflection theory would allow more accurate results at the higher blending angles. Voltage drop by the bending of the fiber is determined from the curvature of the fiber bending.
- The final results of the simulated analytical calculations can then be compared with the experimental results.

Figure 4.6 Displays the simulated local velocity at the point of the fiber on the a) top surface b) bottom surface.

The instantaneous velocity data that was presented in Figure 4.6 uses Equation 3.1 to find out the force that was acting on the fiber. This was done via Microsoft Excel for ease of calculation and tabulation. After the force calculation step, Mathematica® software was used to obtain the relationship between the fiber bend angle ϕ and the force. The details on the

input information and variables can be referred to in Appendix B. Figure 4.7 displays the calculated relationship between ϕ and the angle of AOA.

Figure 4.7 Relationship between AOA and angle ϕ (rad) after deploying Mathematica a) upper surface b) lower surface.

Figure 4.8 Evaluation between theoretical voltage output and angle of attack after a) upper surface b) lower surface.

Figure 4.8 displays the final results obtained from Equations 3.6 to 3.16. A series of trends could be observed throughout the experiment. For example, as the AOA increases from -16° to -4° on the upper surface, the voltage decreases with a gentle slope. Interestingly as the AOA increases from -4° to 10° , the voltage decreases rapidly with a steeper gradient. At AOA greater than 10° , the decrease of voltage slows and seems to have reached a certain limit. The relative change of voltages observed is greater in the far field velocity of 10 m/s compared with 30 m/s. An opposite effect of the voltage drop was observed at the lower

surface of the airfoil. This is due to the blade profile and the aerodynamic properties of the fluid flow.

4.3.1 Experiment

For the wind tunnel tests that are performed on the AOA sensor, wind speeds were varied from 10 *m/s* to 30 *m/s*. At each wind speed, the air profile was actuated from 0° to 16° AOA with 2° interval and stopping for 1 minute to airfoil to settle before moving on to the next angle. The test was also conducted from 0° to -16° AOA.

Figure 4.9 Variation of optical fiber output voltage with FFT smoothing as a function of AOA at the top surface with 2° Angle interval from a) 0°AOA to -16°AOA b) 0°AOA to 16°AOA

From Figures 4.9a and 4.9b, there is a noticeable trend of decreasing voltage output when the angle of attack increases from -16° to 16°. This effect is further enhanced after the data is processed using a 5 point Fast Fourier Transform (FFT) smoothing operation performed by plotting software, Origin Labs. Interestingly, the increase in flow speed from 10 *m/s* to 20 *m/s* and to 30 *m/s* brings about a reduction in the voltage output which can be seen at 0° AOA and the difference in the voltage output is plotted in Figures 4.9a and 4.9b.

In Figures 4.9a and 4.9b, the 10 *m/s* graph has step-like details which showed a distinction between each angle of attack. For the flow speeds of 20 *m/s* and 30 *m/s*, the changes between the AOA was not as distinct from 4° to 16°. Overall, there was still the noticeable behaviour of a reduction of voltage output against increasing AOA. Figure 4.10 averages out the

experimental values and increases the visibility of the stated trend of a declining voltage output.

Figure 4.10 Experimental Averaged Results: variation of voltage with AOA on a) upper surface, b) lower surface

From Figures 4.9 and 4.10, the upper surface of the profile shows a decrease in voltage output with increasing AOA. The higher voltage decrease corresponds to higher bending of the fiber which also suggests a higher increase in the local velocity. The effect on the bottom side of the profile was observed as the reversed effect in which a higher AOA would mean lower local velocity and hence lower bending and a higher voltage output.

4.3.2 Comparison with the experimental and theoretical results

The graphs in Figure 4.11 show the theoretical results using Equation 3.16 and experimental measured voltage drop for the upper and lower surfaces. The results for both theoretical simulation and the actual experiment for the upper pressure side surface display a similar trend of decreasing voltage output when the AOA was increased. For the lower suction surface, there is a positive relationship between the AOA and the voltage output.

Physically this means that for the pressure side, the increase in AOA brings about a rise in force acting on the fiber. This force is due to the drag force as per Equation 3.1, the increment in force also equates to a faster local fluid flow velocity acting on the fiber. The increase in fluid velocity corresponds to an increase in negative coefficient of pressure as per Bernoulli's

equation (in Equation 2.2) and hence confirms the C_p trend presented in Figure 3.7 using Xfoil simulations.

Figure 4.11 Comparison of experimental and theoretical results on a) upper surface, b) lower surface

The theoretical analysis provided a larger drop of voltages at all velocities which equates to a larger bending of the fiber. This is mainly due to the assumption that the drag coefficient remains constant throughout the whole experiment. However experimentally, as the fiber bends, the orientation of the fiber to the air flow changes accordingly to the bending of the fiber. This results in a reduction of the drag coefficient which in turn reduces force acting on the fiber. Therefore the amount of deflection in the actual experiment is lower than the theoretical analysis.

The presence of a fiber in the air flow will also alter the fluid flow path and change the air velocity at the fiber region. The simulation, on the other hand, assumed a smooth laminar flow at the fiber region which would have contributed to the shifts in the simulation results as compared to the actual experimental data.

4.4 Stall detector

For the wind tunnel tests that are performed on the stall detector, wind speeds are varied from 10 m/s to 40 m/s. At each wind speed, the air profile is actuated from 0° to 20° AOA with 4° interval and stopping for 60 seconds to airfoil to reach the steady state before moving on to the next angle.

Figure 4.12 Data captured by the stall detector from 0° AOA to 20° AOA over 4° AOA interval

In analysing the data, a total of 15000 sampling points have been taken at each angle and used to find the average values and the standard deviation.

Table 4.1 Standard deviation and average values of the sampling point at each AOA.

AOA	10 m/s		20 m/s		30 m/s		40 m/s	
	Std dev	Average	Std dev	Average	Std dev	Average	Std dev	Average
0	0.009884	4.539034	0.008259	3.956578	0.008481	3.675932	0.008417	3.551115
4	0.010331	4.535269	0.008423	3.93684	0.008564	3.658794	0.009474	3.452844
8	0.011793	4.528882	0.008426	3.941513	0.008759	3.549921	0.011175	3.37248
12	0.019193	4.566475	0.00906	3.988125	0.017749	3.630606	0.01401	3.393449
16	0.044931	4.84061	0.058877	4.196923	0.037847	3.690452	0.031816	3.493617
20	0.091257	4.82492	0.150634	4.379503	0.310452	4.450449	0.466179	4.276386

It can be noted that as the AOA of attack reaches 16°, the standard deviation increases as seen in Figure 4.12 where the fluctuations increase. When the angle increases further to 20°, the fluctuations increase even more rapidly.

Hence using the controller to monitor the amount of standard deviations, when standard deviations increases till above 0.03 *m/s* or by observing the fluctuations, the stall margin can be detected and pitching of the blade in to the stall region can be avoided. When the standard deviation increases to a certain limit, the blade can be pitched back to avoid stalling.

In addition, from Figure 4.12 and Table 4.1, a large increase in the fluctuation of the data points or signals that are captured can be noticed as the angle of attack increases. It is noted that there are not much fluctuations from 0° AOA to 8° AOA for the flow speeds of 10 *m/s* and 20 *m/s* given that the respective standard deviation is between 0.008V to 0.011V, this can be explained that at such a low AOA and flow speed, the flow across the profile is mostly laminar.

However, when the AOA increases to 12° , the fluctuation increases, and this effect is more evident in the flow speed of 30 *m/s* and 40 *m/s* where the standard deviation increases to 0.014V and 0.018V respectively. This shows that the flow across the profile has already started to separate and the turbulence intensity has increase which causes high fluctuations that was detected by the sensor.

When the AOA increases further to 18° and 20° , the airfoil loses lift and is said to have stalled and there would be very large fluctuating turbulence [67]. At the stalled flow condition, the device displayed high fluctuations of the voltage output and the average value reverts to 5V, which is the starting value of fibre in initial state. This high amount of fluctuation in the standard deviation from 0.15V to 0.466V shows that the fiber is bending forcefully, indicating that the increased air flow circulation which causes the increased fluctuations. Therefore with this optical fibre sensor stall can be determined by focusing on its voltage fluctuation.

To sum up, the results produced by the AOA sensor have proved to be promising and the results have distinct “steps” which facilitate the determination of the AOA at the output data. The stall detector was able to “sense” a stalling effect, i.e. and increased turbulence effect by observing the fluctuation. Therefore these two techniques can be applied in the actual wind turbine for further testing and validation.

4.5 Analysis of the fluctuating motion

An Ansys fluid structure interaction (FSI) analysis was carried out to predict the behaviour of fiber under the effects of flow across the airfoil. A transient Fluent model and Ansys mechanical model was implemented in the fluid-structure interaction simulation. As it is a transient simulation, when the air (fluid) passes cross the fiber and it creates a force on it: in response the fiber would bend over and over-shoot its steady state position. This movement took 20.8 *ms*.

Figure 4.13 Demonstrates the simulated fluid-structure interaction with Ansys Workbench.

Figure 4.13 demonstrates the simulated fluid-structure interaction with the Ansys Workbench at different times of the simulation. The simulation illustrates that the fibre takes 0.0918 s to reach its steady state position. From the actual experimental raw data, fluctuation of the results was observed. This was attributed to the wind tunnel measuring instrument's accuracy of 0.01 m/s and the variation of flow rate in the wind tunnel with a standard deviation of 0.02 m/s . Since the measuring instrument has the capability to measure up to 1 kHz , equivalent to 0.001 s , it is able to record the finest bending motion of the fiber including the variation from the experimental setup.

Chapter 5

Conclusions and Scope for Future Work

It was first established that there is a need to reduce the cost of energy for wind turbines. This project aims to improve the situation by developing a local blade flow sensor that overcomes the practical drawbacks of existing flow measurement devices for active control. Current flow techniques are unable to fulfil the design requirements when placed near the blade tip of the wind turbine. The four key design requirements for a flow sensor on a wind turbine blade are lightning attraction issues, high reliability, high accuracy and low cost. The existing measuring techniques are unable to deliver a good balance between these four design requirements as discussed in Chapter 2. A brief summary of all the existing wind sensing techniques is described below:

- The mechanical anemometer has the problem of reliability due to moving parts although it requires low cost for setup.
- The pitot static tube though cheaper, may get clogged with dust.
- The sonic anemometer can measure wind speeds accurately but is expensive.
- The laser anemometer gives accurate flow measurements, but expensive to own and maintain.

With the motivation to drive the improvement of the wind measurement techniques forward, an optical fiber velocimeter was presented as a viable flow measuring method after careful study of its capabilities and potential to fulfil the key design requirements were conducted. Despite lack of development in this field, the optic fiber measurement model was found to excel in its potential to be used on the wind turbine blades. For example, it has excellent resilience against lightning attraction and other environmental conditions that it is subjected to when placed on a wind turbine in wind farms. The weight index based scoring system ranked fiber optics based flow meter as the most suitable wind sensing technique with the highest score in design matrix summarised in Table 2.1.

The project started off to develop the single bending fiber optics before implementing the fiber model onto the aerofoil and studying the system's feasibility. Two competing modes of sensing techniques were studied. First, the fiber optics stall detector was designed to pitch the blade to the maximum Angle of Attack (AOA) before stall occurs. The second technique

describes the use of the optical fiber as an AOA sensor that can determine the angle of attack and to correctly pitch the blades to the optimum AOA. Hence, both techniques have shown their potential in the improving energy production.

The Xfoil based computational fluid dynamics simulation has allowed a definition of the placement of the sensor on the wind turbine blades. The angle of attack sensor position was set to be near the leading edge where the pressure difference between each angle of attack was large enough to be captured. The experimental results were able to validate the simulation's optimal sensor position and also confirm the optic fiber sensor's potential as an AOA sensor to pitch the blade for maximum power production. It shows the differentiation of each angle of attack at a 2° interval. It can be concluded that the fiber optic sensor can be deployed as an angle of attack sensor with most favourable location to be near the leading edge.

In the experiment using the fiber optics sensor as a stall detector, the fiber was able to detect a significant increase in fluctuation at the point of stalling, i.e. increased turbulence which will lead to a drastic drop in power production by the wind turbine blades. By positioning the fiber optic sensor near the trailing edge, the sensor can operate as a stall detector and prevent any stalling and power loss.

The author recommends using both the AOA sensor and the stall detector on the wind turbine blade as this will produce a robust system for optimal power production by the wind turbines. Both systems can work together to bring the wind turbine power production to a whole new level of improved efficiency in power production and cost of energy.

5.1 Scope for Future work

There are many reviews and reports stating that the two-dimensional flow modelling is not precise enough to describe the flow to the irrotational effects and the coriolis force. The aim of this project was to study the viability of using fiber optics in certain wind turbine applications. It has been proven that there is great potential in furthering this study. Hence the author recommends that a more detailed study of three dimensional analysis can be employed in the laboratory test turbine.

Certain aspects of this project can be further developed. The analysis for the finite strain was based on a concentrated load due to a limitation of resources. For improvements in the analysis, a skewed distributed load analysis could be performed.

It is noted that the Young's Modulus that was implemented in the theoretical derivations of the equations was based on a few references provided. Proper investigation techniques such as the vibration reed could have been implemented to determine the actual young's modulus. This can further improve the reliability of the theoretical analysis. In addition, using the vibration reed, the resonance of the fiber could also be determined. By determining the resonance frequency and the vibration mode of the fiber, by knowing such information, the use of the information at the resonant frequency should be avoided.

The fluid structure interaction was performed via a uni-directional flow for an initial understanding of the fiber behaviour and results. In an actual application, three dimensional flow model would be more applicable.

In Chapter 4, the interaction between the flow and the fiber was not considered. A recommendation will be to include the fluid structure interaction (FSI) modelling with a NACA profile instead of the straight profile presented in Section 4.6.

This project has completed mainly the initial experimental work and the simulation trials. To develop this technique to practical usage, the fiber optic flow sensor should be integrated with an active closed-loop feedback system. Doing so would determine the feasibility of such closed-loop system and the overall amount of increased power generation in implementing such technique.

With this future work, the project will be able to develop this first conceptual design and initial prototype in this report into a measurement model more representative of the forecasted design.

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Appendix A

Fluid dynamics is about the study of fluid motion. The equations formed in the fluid dynamics are based on the physical laws of conservation[56], namely,

- 1) Conservation of Mass (Continuity equation)
- 2) Conservation of Linear Momentum (Newton's second law of motion)
- 3) Conservation of Energy (First law of thermodynamics)

A1. Forces acting on a fluid element [56]

The diagram above illustrates the different forces that is acting on an element. Two scientists, Claude-Louis Navier and George Gabriel Stokes managed to describe the fluid motion using the conservation laws with Newton's second law to derive the equations as what we know as now the Navier -stokes equation [56].

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(2\mu \frac{\partial u}{\partial x} + \lambda \nabla \cdot \mathbf{v} \right) + \frac{\partial}{\partial y} \left(\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \frac{\partial}{\partial z} \left(\mu \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right) + \rho g_x \quad (\text{A1})$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right) + \frac{\partial}{\partial y} \left(2\mu \frac{\partial v}{\partial y} + \lambda \nabla \cdot \mathbf{v} \right) + \frac{\partial}{\partial z} \left(\mu \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \right) + \rho g_y \quad (\text{A2})$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left(\mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right) + \frac{\partial}{\partial y} \left(\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right) + \frac{\partial}{\partial z} \left(2\mu \frac{\partial w}{\partial z} + \lambda \nabla \cdot \mathbf{v} \right) + \rho g_z \quad (\text{A3})$$

The equations above describe the equilibrium equations in 3 direction, x, y and z.

Appendix B

Computation simulation – Ansys work bench / fluent

Snap shot of the Design modeller to input the model and to break up the sector into 4 quadrants.

View of the setting of the meshing tool provided by Ansys work bench.

Settings deployed in fluent

Comparison of the simulated results with [59].

Mathematica Program

```
Export["file.xls", {NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}], {a, 0, 2}], "XLS"]

SyntaxError: "Export[file.xls," cannot be followed by "NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}], {a, 0, 2}], XLS]".
SyntaxError: "NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}], {a, 0, 2}" is incomplete; more input is needed.
SyntaxError: Incomplete expression; more input is needed.

In[ ]:= Table[1, 2]
TableForm: Argument 2 does not have the correct form for an iterator.

In[ ]:= NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}], {a, 0, 2}

SyntaxError: "a = NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}], {a, 0, 2}" is incomplete; more input is needed.
SyntaxError: Incomplete expression; more input is needed.

In[34]:= data = Cases[Plot[NIntegrate[1/Sqrt[Sin[a] - Sin[x]], {x, 0, a}]/2]^2, {a_, 1.75, 3}], Line[data_] := data, -4, 1][[1]]

NIntegrate::slown: Numerical integration converging too slowly; suspect one of the following: singularity, value of the integrand is 0, highly oscillatory integrand, or WorkingPrecision too small.
NIntegrate::eub: NIntegrate failed to converge to prescribed accuracy after 9 recursive bisections in a near {x} = {1.38452}. NIntegrate obtained 4.27343 - 4.54111 I
and 0.2633284366189185` for the integral and error estimates.

Part::part: Part 1 of {} does not exist.

In[35]:= Export["file.xls", data, "XLS"]
Out[35]= file.xls

Plot[data, PlotRange -> All]
PlotArg: Plot called with 1 argument; 2 arguments are expected.
Plot[data, PlotRange -> All]
```