DEVELOPMENT OF THE USM WIND TUNNEL VALIDATION MODEL FOR CALIBRATION

by

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ENDORSEMENT

I, Sim Chiow Moon hereby declare that all the corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date:

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

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DEVELOPMENT OF THE USM WIND TUNNNEL VALIDATION MODEL FOR CALIBRATION

ABSTRACT

Wind tunnel is a device which plays the important role in the study of effect of a moving object through air stream. It generates the air flow which simulates the wind flow condition. The performance of wind tunnel is always a factor to be concerned. A good flow quality in test section can be surely reduce the uncertainty in the experiment conducted, and hence, increase the repeatability and reliability for the experimental results. Calibration of wind tunnel should be emphasized in the laboratory to maintain the flow quality in the test section. The development of a standard model for USM wind tunnel calibration is researched in current project. The standard model will need to possess a valid experimental data for a wind tunnel experiment. The main objective to be attained is to establish a standard model for the wind tunnel calibration. In current research, it is important to study the pressure distribution on the selected wing model for a range of angles of attack and then further investigate on the lift contribution for the model by integrating the pressure distribution. The obtained experimental results will be analyzed and validated by comparing with other wind tunnel data for similar model and conditions. In brief, NACA 2412 infinite wing model is researched in this FYP work. The model was pressure tapped with 33 pressure taps on upper surface and lower surface. All the instruments involved in the experiment was initially calibrated to avoid displeased uncertainty in the experiment. The experiment was conducted under incompressible flow. Pressure distribution at various angles of attack were measured and lift contribution was computed for the model. Experimental data was then validated

with reference data and discrepancy on the experimental data was identified. The pressure distribution on the upper surface of the model did not reach a good agreement with reference pressure distribution for the upper surface. However, the pressure distribution of lower surface measured from experiment agreed well with reference data. The finding from discrepancy analysis experiment indicates that the discrepancy might cause by the deterioration of the pressure taps at the inner assembly of the model which it can’t be checked due to the disassemble design of model. Further recommendations are also given based on the improvement on the model accuracy measurement, qualitative measurement and validation method for future research.

PENGEMBANGAN MODEL STANDARD UNTUK PENENTUKURAN TEROWONG ANGIN USM

ABSTRAK

Terowong angin adalah peranti yang memainkan peranan penting dalam mengkaji kesan objek bergerak melalui aliran udara. Ia menjana aliran udara yang menyerupai keadaan aliran angin. Prestasi terowong angin sentiasa menjadi faktor yang perlu diambil perhatian. Kualiti aliran yang baik dalam seksyen ujian pasti dapat mengurangkan ketidakpastian dalam eksperimen yang dijalankan, dan karenanya, meningkatkan kebolehulangan dan kebolehpercayaan untuk keputusan percubaan. Penentukuran terowong angin perlu ditekankan di makmal untuk mengekalkan kualiti aliran di bahagian ujian. Pengembangan model standard untuk penentukuran terowong angin USM diteliti dalam projek semasa. Model standard perlu mempunyai data eksperimen yang sah untuk eksperimen terowong angin. Objektif utama untuk dicapai ialah untuk menubuhkan model standard untuk penentukuran terowong angin. Dalam penyelidikan semasa, adalah penting untuk mengkaji pengagihan tekanan pada model sayap terpilih untuk pelbagai sudut aliran udara dan seterusnya menyiasat sumbangan lif bagi model dengan mengintegrasikan pengagihan tekanan. Hasil eksperimen yang diperolehi akan dianalisis dan disahkan dengan membandingkan data terowong angin lain untuk model dan syarat yang sama. Ringkasnya, model dengan aerofoil NACA 2412 akan dikaji dalam kerja FYP ini. Model itu telah dipasang dengan 33 tekanan paip pada permukaan atas dan permukaan rendah. Semua instrumen yang terlibat dalam eksperimen pada awalnya ditentukur untuk mengelakkan ketidakpastian dalam eksperimen. Eksperimen ini dijalankan bahawa aliran tidak dapat dikompresikan.

Pengagihan tekanan di pelbagai sudut aliran udara diukur dan sumbangan lif dikira untuk model. Data eksperimen kemudian disahkan dengan data rujukan dan percanggahan pada data eksperimen telah dikenalpasti. Pengagihan tekanan pada permukaan atas model tidak mencapai persetujuan yang baik dengan pengagihan tekanan rujukan untuk permukaan atas. Walau bagaimanapun, pengagihan tekanan permukaan bawah yang diukur dari eksperimen dipersetujui dengan baik dengan data rujukan. Hasil daripada analisis percanggahan menunjukkan bahawa percanggahan mungkin disebabkan oleh kemerosotan tekanan paip pada pemasangan dalaman model yang tidak dapat diperiksa kerana reka bentuk model pembongkaran. Cadangan yang lebih lanjut juga diberikan untuk penambahbaikan berdasarkan ketepatan model pengukuran, pengukuran kualitatif dan kaedah pengesahan untuk penyelidikan masa depan.

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LIST OF ABBREVIATIONS

AGARD	: Advisory Group for Aerospace Research and Development
ASEE	: American Society for Engineering Education
CCWT	: Closed Circuit Wind Tunnel
CFD	: Computation Fluid Dynamics
FYP	: Final Year Project
MIRA	: Motor Industry Reseach Association
NACA	: National Advisory Committee for Aeronautics
NASA	: National Aeronatics and Space Administration
NAL	: National Aerospace Laboratory
ONERA	: Office National d'Etudes et de Recherdes Aerospatiales
SERC	: Science and Engineering Research Center
USB	: Universal Serial Bus
USM	: Universiti Sains Malaysia

LIST OF SYMBOLS

C	: Chord length, m
C_p	: Pressure Coefficient
C_l	: Lift coefficient
$C_{l_{max}}$	: Maximum lift coefficient
dx	: Change in horizontal distance, m
ρ	: Air density, kg/m^3 (ρ = 1.225 kg/m^3 at sea level)
$p_{stagnation}$	: Stagnation pressure, Pa
p_∞	: Static pressure, Pa
q_∞	: Dynamic pressure, Pa
Re	: Reynolds number
μ	: Dynamic viscosity of air, kg/ms (μ = 1.789x10^{-5} kg/ms at sea level)
V_∞	: Free stream velocity, m/s
X/C	: Current x-coordinate-to-chord ratio

CHAPTER 1

INTRODUCTION

1.1 Overview

Wind tunnel simulates the air movement which enables the researchers to study the flow behavior around the objects of interest. By investigating the flow behavior, researchers are able to assess the forces acting on the object and their interaction with the flow. In the early decades, wind tunnel was designed as a device to investigate the aerodynamic theories and facilitate the innovation of an aircraft. Instead of playing its important role in the Aerospace industry, the application of wind tunnel for aerodynamic research is also widely expanding in nowadays for other fields including automotive industry, architecture, education, etc. The flow quality in the test chamber of a wind tunnel is crucial to define the performance of the wind tunnel. With this fact, maintenance of wind tunnel has raised the concerned from researchers to maintain wind tunnel's flow quality.

Calibration is the comparison between the standard measurement and the measurement from the instrument which is suspected to be out of calibration. It is one of the major processes which is done to maintain the accuracy of an instrument. This configures the instrument to provide the measurement results for any specimens within an allowable range. A good calibration process will minimize the factors which might lead to the instrument inaccuracy measurements. Hence, it maintains the performance of the instrument. The calibration of a measuring instrument is generally conducted periodically, either annually, quarterly or monthly, according to the user's requirements or recommendation from the manufacturer.

The calibration of wind tunnel has become one of the concerns in the wind tunnel design. A specially constructed calibration methodology is made for each wind tunnel model as to maintain the reliability of the wind tunnel. It helps to reduce the maintenance costs from manufacturing errors of a wind tunnel. Additionally, the calibration laboratory is also served to maintain certification of wind tunnel. Calibration methodology is implemented in a time frame, either short term or long term to check the performance of the wind tunnel regularly.

Among the wind tunnel calibration techniques available, standard model calibration method is considered one of the widely implemented techniques by the researchers. The non-dimensional aerodynamic coefficients of the standard model under certain flow conditions were established as the standard measurement in the wind tunnel calibration event to assess the performance of the wind tunnel. The outcome from the comparison between the standard and measurement from the wind tunnel under test can be further justify on any of the adjustment should be made on the tested wind tunnel to correct the error to a tolerable level.

In present, there are some standard models which available for the study of aeronautics, such as the model AGARD-B, ONERA-M, HB-2, etc (Damljanovic, et al., 2006; Jr, 1976; Gray, 1964). Besides, standard model such as MIRA reference car and Ahmed body has used in the calibration of wind tunnel which designed to perform road vehicles aerodynamic testing (Good & Garry, 2004).

Development of a wind tunnel standard model is a long-term process to ensure the aerodynamic performance of the model is excellent and measurement is reasonable and reliable. For current research, it begins with the calibration of the instruments which would be used in the experiment. This checking is helped to prevent any undesired error arise during the experiment. The study of aerodynamic characteristics including pressure distribution and lift coefficient of the selected model only be conducted after the instruments calibration is done. In the next stage, the experimental results are validated with reference data. Discrepancy is observed and further justification on the source of discrepancy is made.

1.2 Motivation

Wind tunnel with good performance possesses the scopes including the ability to provide reasonable Reynold's number range, uniformity of test section flow and insignificant turbulence intensities, is highly demand in the research of fluid phenomena. The calibration process is required to be performed in a timeframe, which could be in short term or long term, as to ensure the performance of the wind tunnel. Nonetheless, the appointment service provided by seller for wind tunnel calibration may consume time in waiting the service and delay the project timeline. Hence, it is suggested that for the wind tunnel user to establish a simple and effective wind tunnel calibration technique to conduct calibration for their wind tunnel. In conjunction with this intention, a research to develop the standard model for wind tunnel calibration can be initiated.

The measurement of a standard model is a fundamental reference measurement for a wind tunnel calibration. The need to identify the accuracy and uncertainty on a targeted standard model is essential in developing a consistent and comparable standard. A good standard will need to possess a confidence level of measurement which has known accuracy and uncertainty. As the study of accuracy and uncertainty of standard model measurement is needed, it is important to study the fundamental aerodynamic of the standard model in the early research for further development.

1.3 Objectives

The main objective to be achieved in this project is to establish a standard calibration model for the wind tunnel maintenance. In present study, the research objectives are narrowed to as followed:

- To obtain the pressure distribution on the selected wing model for a range of angles of attack and investigate the lift contribution for the model.
- To analyze and validate the experimental data by comparing with other wind tunnel data for similar model and conditions.

1.4 Thesis Organization

This thesis is arranged in six chapters. In Chapter 1, it provides the overview on the topic of this project. Motivation and objectives are also stated to define the scope of the project. Meanwhile, the literature review on the project title are further discussed in Chapter 2. Next, Chapter 3 details the fundamental theory of the aerodynamic of an airfoil which is applicable in this project. While in Chapter 4, it describes the procedures undertaken in detail throughout the project. Overall experimental setup is also introduced in this chapter. In Chapter 5, results obtained for all stages of experiment are presented, followed by the findings from the results obtained are discussed. For the last chapter which is Chapter 6, conclusion is made for the whole project conducted. Some suggestions are also proposed in Chapter 6 to make improvement in future research for this subject.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the initial studies on the project title before the research is conducted. The study was focused into three fields including development of wind tunnel calibration, introduction to standard model calibration technique and development of pressure tapping measurement. Further discussion on the airfoil pressure distribution measurement by pressure tapping technique was also presented in the following section. All reviews from the relevant literature were contributing the confidence to proceed the research.

2.1 Development of Wind Tunnel Calibration

The wind tunnel calibration involves in determining the mean values and uniformity of various flow parameters in the region to be used for model testing, also known as test section. In any of wind tunnel calibration, the basic parameters which are taken into concerns including stagnation pressure, test section temperature, air velocity or Mach number, and flow angularity. There are also flow conditions which interest in a wind tunnel calibration such as turbulence and the extent of condensation or liquefaction (Pope, 1961).

Considering the calibration for a low speed wind tunnel, it is generally conducted in a range which is not pertaining to the compressibility effect of flow. The Reynold’s number is the parameter to be emphasized instead of Mach number (Pope, 1961). Thus, the fundamental principles applicable in modelling low speed aerodynamic flow including mass conservation, force and motion relating to the Newton's Second Law and energy exchanges governed by the First Law of Thermodynamics (Barlow, et al., 1999).

In a test section flow calibration, the flow behaviour in the test section is emphasized. Few scopes which are commonly focused as followed:

- Flow speed setting
- Flow Angularity
- Turbulence

2.1.1 Flow Speed Setting

The pitot-static tube can be used to measure the air speed in the test section when there is no model installed in the test section. However, it was found that when there is test object in the test section, it will cause induced flow. Thus, to avoid the effect of induced flow, total pressure is recommended to measure in the settling chamber ahead of contraction cone which is the location L as shown in Figure 2.1. Meanwhile, at location ahead of the test section, location S, static pressure is measured. Since the velocity is not uniform in the test section, further survey on the flow uniformity can be done (Barlow, et al., 1999).

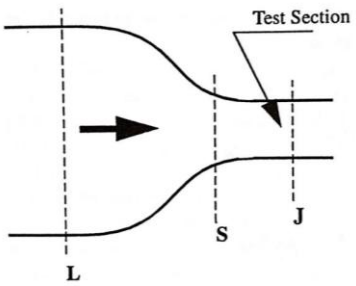

Figure 2.1: Schematic diagram of settling chamber (L), contraction (S) and test section (J) in wind tunnel (Barlow, et al., 1999).

2.1.2 Flow Angularity

There are some vortexlike flow available in the test section. This results in the poor velocity distribution in the test section. The non-uniform distribution of velocity can occur due to either poor vane design or improperly adjusted vanes that cause the flow to over or under turn. A variation of upflow across the span of a wing results in an effective aerodynamic twist, whereas the cross-flow region across test section in the region of the vertical tail will change the slope of the yawing moment versus side slip or yaw angle (Barlow, et al., 1999).

The basic instrument for measuring the flow angle in a wind tunnel is yawmeters, which consists of some simple symmetric aerodynamic shape including sphere, cone and wedge. Yawmeter is calibrated by being pitched and yawed in the airstream and the pressure differentials across opposite holes recorded (Pope, 1961). Nowadays, hot wire anemometer is commonly used in measuring the changes in flow angularity (Ristic, et al., 2004). The heated sensor is a thin and short wire which generally made of tungsten coated with platinum. With the small dimensions, it is applicable to response very fast to measure the local velocity and hence compute the flow angle in wind tunnel (Comte-Bellot, 1976).

2.1.3 Turbulence

Turbulence in the test section often brings effect to the experimental results in different wind tunnel test although the experiments are conducted under the same Reynold's number and conditions. It has been argued that existence of turbulence has caused test section possesses the flow pattern which is similar to the flow pattern in free air at a higher Reynold's number. Hence, it results in the higher "effective Reynold's number" for the experiment (Barlow, et al., 1999).

Turbulence sphere was introduced as the primary way to measure relative turbulence of a wind tunnel. The critical Reynold's number of the turbulence sphere can also be measured. Nevertheless, the use of turbulence sphere only yields what may be thought of as an average value of tunnel turbulence (Barlow, et al., 1999). The relation between critical Reynold's number of turbulence sphere and turbulence intensity is further measured using hot wire anemometer (Dryden & Kuethe, 1929; Dryden, et al., 1937).

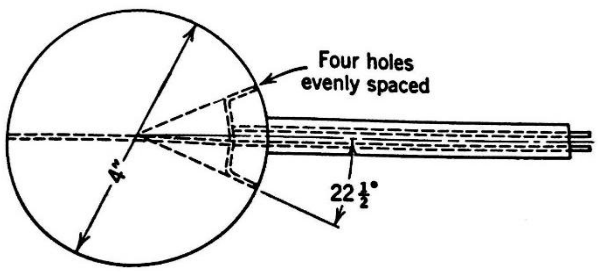

Figure 2.2: Turbulence sphere (Barlow, et al., 1999).

2.2 Introduction to Standard Model Calibration Technique

One of the wind tunnel calibration techniques which was worth to study was standard model calibration technique. Standard model was established for the purposes including:

i) confirmation of the reliability of the respective wind tunnel by comparing the test data with other wind tunnel data with similar model and experiment conditions, and

ii) check of data repeatability over time and after major modifications of the tunnel (Watanabe, et al., 2003).

Standard model calibration on the wind tunnel in NAL's Wind Tunnel Technology Centre (WINTEC) in Japan was performed to certify the overall reliability of wind tunnel data by comparing with other tunnel data which acquired by other wind tunnel. Data consistency also took into concerned between different-speed-range tunnel in WINTEC during the standard model calibration. Three standard models including ONERA M-series model, AGARD-B calibration model and HB-2 model were considered in this research due to the high availability of precise configuration data for the model. Each model design for different experiment conditions. ONERA M-series model was chosen for subsonic to transonic speed ranges, AGARD-B calibration model was performed under transonic to supersonic regimes, while HB-2 model calibration experiment was conducted for transonic through hypersonic speed ranges (Watanabe, et al., 2003).

Figure 2.3: ONERA M-series standard model in low speed wind tunnel (Watanabe, et al., 2003).

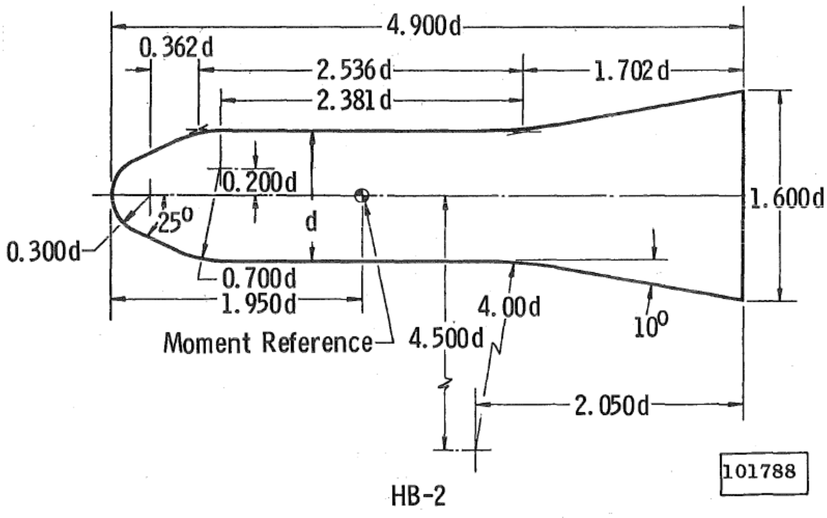

Figure 2.4: HB-2 model configuration (Gray, 1964).

The standard model calibration technique was widely developed for the calibration of T-38 wind tunnel from Military Technical Institute (VTI) in Belgrade to ensure the wind tunnel operates in a proper manner (Hills, 1961; Damljanovic, et al., 2006; Damljanovic, et al., 2013; Damljanovic, et al., 2012; Damljanovic, et al., 2017). The standard model was introduced as the Advisory Group for Aerospace Research and Development (AGARD) calibration model. During the early stage, AGARD calibration models including model A, model B, model C, model D, model E and model F were designed for different test nature and measurement. Every model excluded model F were tested in different wind tunnel and the discrepancy of data obtained was reviewed (Hills, 1961).

AGARD-B model which fabricated by Boeing, USA, was the standard model for the T-38 trisonic wind tunnel calibration event (Damljanovic, et al., 2006; Damljanovic, et al., 2013; Damljanovic, et al., 2017). AGARD-B model test was conducted with the same methodology and under the similar conditions as previous experiment. The repeatability conditions were the same measurement procedure, same measuring instruments used under the same conditions, same locations and repetition over a short period of time (Damljanovic, et al., 2013). The repeatability can be defined as the closeness of the agreement between the results of successive measurement of the same measure and carried out under the same conditions of measurement (Hemsch, et al., 2000).

The test results from previous T-38 trisonic wind tunnel calibration method was further evaluated. The evaluation included the details of experiment such as test facility, data quality assurance, measurement uncertainty, measurement repeatability, and the data validity. It was concluded that the Mach number and the flow angle are the critical measurements which would directly affect the aerodynamic coefficients calculation. This research had confirmed that the high quality of wind tunnel, instrumentation and data processing was being maintained (Damljanovic & Rasuo, 2010).

For further studies, a research was also conducted by combining the experimental and numerical procedure (CFD) to determine and estimate the subsonic and supersonic aerodynamic behaviour of an AGARD-B model with a non-standard nose configuration. It was found that the comparison between experimental and numerical results reached a good agreement. This research indicated that CFD is applicable for assessment procedure of diverse geometry types that often cannot be sufficiently covered by measurements (Vidanovic, et al., 2014).

Figure 2.5: AGARD-B model in the T-38 wind tunnel test section (Damljanovic, et al., 2017).

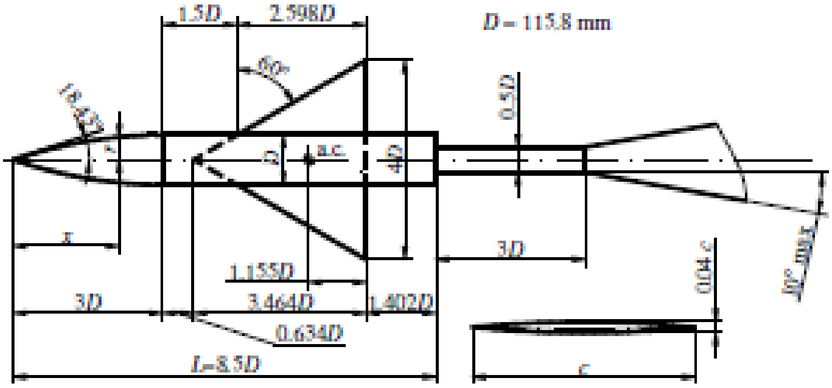

Figure 2.6: AGARD-B model with overall geometry (Damljanovic, et al., 2013).

Figure 2.7: The T-38 trisonic blowdown wind tunnel (Damljanovic & Rasuo, 2010).

2.2.1 Further Study - Computational Fluid Dynamics (CFD) Simulation

The development of numerical method on wind tunnel validation studies has notably growing. It was often combined with the physical experimentation for the wind tunnel simulation data assessment. A low speed wind tunnel was designed and the method of using Computational Fluid Dynamics (CFD) simulation to validate wind tunnel test section flow characteristics was introduced (Calautit, et al., 2014). There was also a research on designing and optimising the two-dimensional contraction of open circuit wind tunnel by using CFD predictions (Sargison, et al., 2004). In these cases, calibration of both designed wind tunnels was made according to the CFD simulation results obtained (Calautit, et al., 2014; Sargison, et al., 2004).

Another calibration techniques can be mentioned was by using CFD simulation wind tunnel data to validate the performance of that wind tunnel. Experimental measurements using the research wind tunnel were performed to verify the CFD model and simultaneously calibrate the facility. The calibration measurement for verification of CFD wind tunnel model included time mean flow, wall shear stress, flow direction and streamwise turbulence intensity in the test section (Sargison, et al., 2004). A wall tapping in the plane of the pitot tube also included in the calibration measurement to measure static pressure. Reference static pressure were measured at the start and end of the contraction respectively (Sargison, et al., 2004). In the end of research, it was found that the CFD simulation technique may be used for future wind tunnel design and calibration due to its reliability.

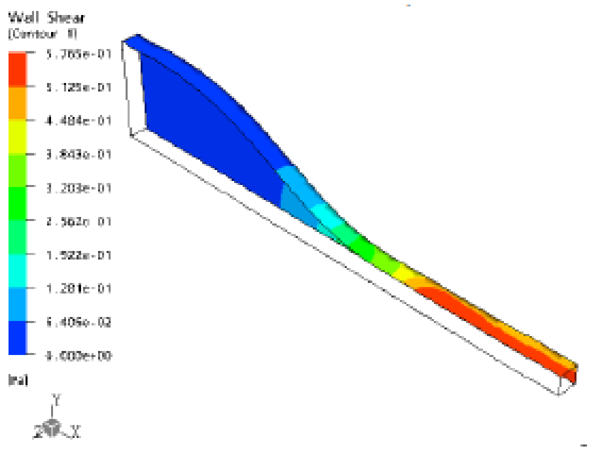

Figure 2.8; Wall shear model simulatio (Sargison, et al., 2004).

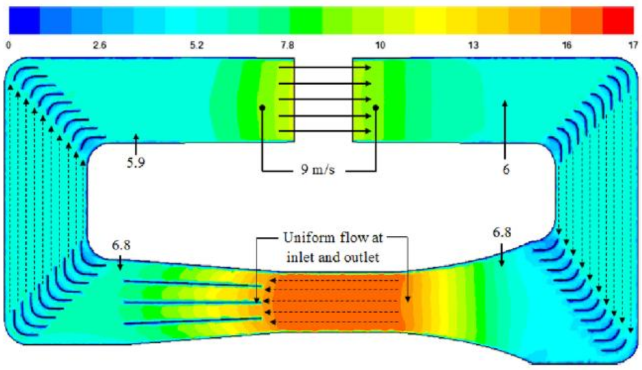

Figure 2.9: Contours of velocity magnitude for wind tunnel configuration with upstream and downstream guide vanes (Calautit, et al., 2014).

2.2.2 Check Standard

The check standard was emphasized in the Langley's framework. The check standards are used to determine the measurement uncertainty and to remove any doubt that the measurement process is stable and meaningful in a statistical sense. There were three key events associated with the check standard which are:

- selection and care of the standard
- selection of test matrix for check standard testing
- test data analysis

The guidelines proposed from the Langley's framework can be referred when deciding the check standard for the research (Hemsch, et al., 2000).

The goal regarding the wind tunnel data was to use the data with confidence, without having inaccuracies or imprecision obscure or preclude achieving the research objectives (Steinle & Stanewsky, 1982). This implies that the inaccuracies in an experiment must be eliminated to achieve the optimum aim of the research. Instead of stepwise improvement made which only focus at one location, identifying and eradicating the poor flow quality around the circuit of the source is a much better attempt (Owen & Owen, 2008). This suggestion could take into consideration during the calibration of a wind tunnel in future work. The test section flow quality also investigated to be influenced by the presence of guide vanes (Calautit, et al., 2014). This evidence could take under advisement for future wind tunnel calibration to enhance airflow uniformity.

2.3 Development of Pressure Tapping Measurement

Wind tunnel measurement has widely conducted through years to investigate the airfoil characteristics. During 20th century, flush static orifice and external orifice were used to measure and investigate the pressure distribution of an airfoil (Montoya & Lux, 1975; Ward, et al., 1983). Flexible tubes or banks of tubes were attached to the wing surface together with the static orifice spaced along the tubing. All the flush static orifices were installed normal to the wing surface. Comparison for the measured pressure distribution obtained with flush and external tubing orifices were made. It was found that the pressure coefficient obtained using both methods achieved satisfied agreement (Montoya & Lux, 1975). It was also verified that both methods also met good agreement with theoretical lift coefficient, C_l prediction (Ward, et al., 1983).

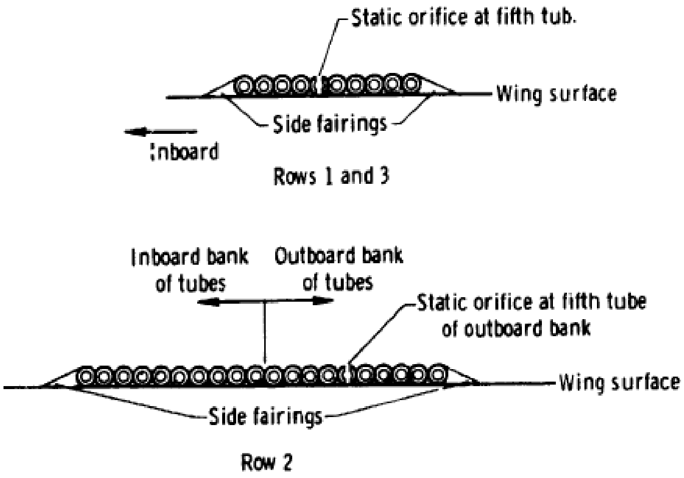

Figure 2.10: Cross sections view of external tubing orifice installation (Montoya & Lux, 1975).

Pressure belts which adhered with number of tubes were also utilized to measure the chordwise pressure distribution for the upper and lower surface of wing in a flight test for the purpose to determine the shock waves location. The pressure belts were bonded on the wing surfaces to obtain surface static pressure. The fairing of pressure belts to wing was accomplished by using a fuel tank sealant to create ramp flush to the top of the pressure belts. The pressure belts were not wrapped around the wing leading edge which would cause crimping and warping (Landers, et al., 1997). In addition, wrapping pressure belts around leading edge would alter the pressure sensed and fail in obtaining reasonable results (Montoya & Lux, 1975). The outcome from this research had pointed out that the accuracy of the pressure measurements has its limitation. The factors including lifting of the pressure belts in localized area and localized crossflow angles which were too severe for the accurate use of pressure belts (Landers, et al., 1997).

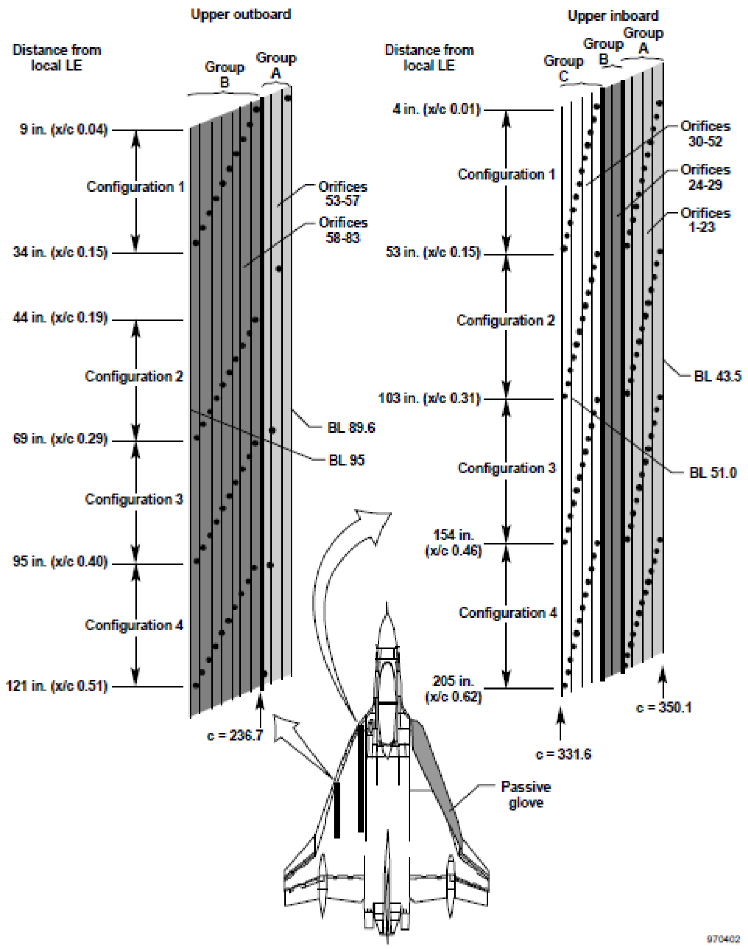

Figure 2.11: Pressure belts layout for wing upper surface (Landers, et al., 1997).

This pressure measurement method was further enhanced and developed to airfoil pressure tapping technique to achieve a higher precision test model which pressure belts initially adhered on the model surface was replaced by pressure taps which installed in the model. Small holes were drilled perpendicular to the surface of the airfoil according to the location of which pressure will be measured. Pressure taps were installed for each hole. Pressure taps were measuring the static pressure on the wing surface according to Bernoulli's principle which will be discussed in Chapter 3. Each pressure taps were then connected to pressure transducer to record the pressure in the hole (National Aeronautics and Space Administration (NASA), 2015).

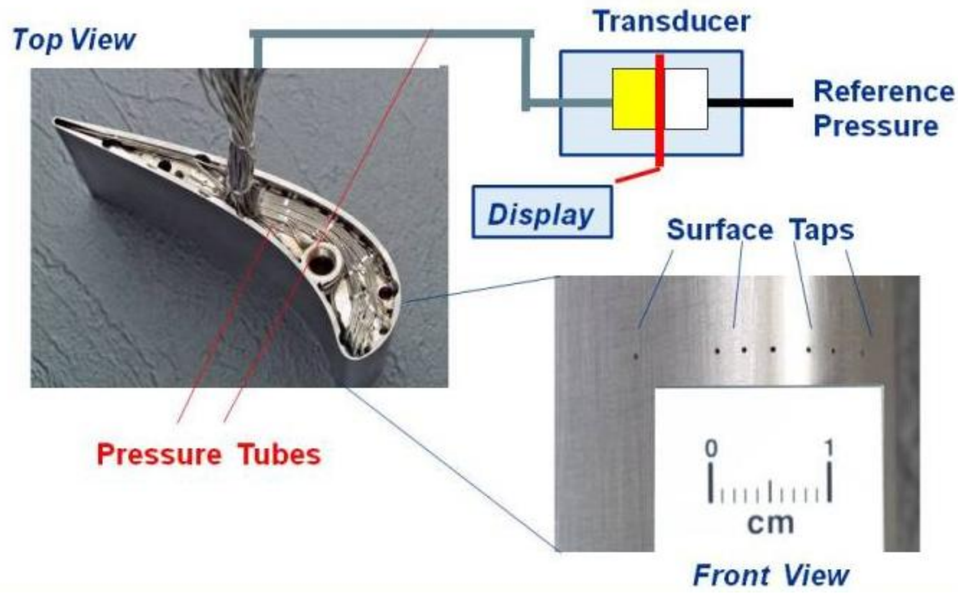

Figure 2.12: Schematic diagram for pressure tapped turbine blade connection with pressure transducer (National Aeronautics and Space Administration (NASA), 2015).

The effect of pressure taps on the measurement of airfoil lift coefficient were also investigated. Three pressure taps with different diameter were installed at the same streamwise location. The research had proved that the pressure tap size does affect the pressure measurement and measured lift curve when the boundary layer is turbulent (Kuester, et al., 2016).

2.4 Relevance of Literature Review with Current FYP Work

In early stage of AGARD-B model development, the lift, lift-curve slope, moment, neutral point, forebody drag and base drag were compared to obtain the reliable measurement as to establish as the standard in wind tunnel calibration. The factors that lead to discrepancy were discussed. A "reference curves" were established from AGARD-B testing after considering the factors such as tunnel-wall interference, sting interference, Reynold's number and the method of fixing boundary layer transition.

The other experimental data using AGARD-B model were then compared to the established "reference curve" (Hills, 1961). As to establish a check standard, the selection of standard, selection of test matrix and test data analysis has to be conducted (Hemsch, et al., 2000). In current study, the model for this reference is selected and the experiment conditions is fixed. The experiment is conducted under incompressible flow. The pressure distribution and lift curve of model is examined. A compatible reference data is acquired from other wind tunnel data with similar model and flow condition. Comparison of experimental data with reference data is made to validate the results. Sufficient experiments should be performed to make justification on the discrepancy of data. This helps to make further improvement on the model and experiment.

CHAPTER 3

THEORY

This chapter discusses the theoretical background study of an airfoil pressure distribution. Mathematical equations related to airfoil pressure distribution including pressure coefficient and lift coefficient are presented. The design concept of a pitot tube for airspeed measurement is also discussed in this chapter.

3.1 Bernoulli's Principle

Bernoulli's equation has widely applied in fluid dynamic field of study. The Bernoulli's principle insists that when the velocity, V increases, the pressure, P decreases, and vice versa. This principle is only applicable for isentropic flows, which the flow is defined to be adiabatic and reversible. The effect of irreversible processes and non-adiabatic processes are small and can be neglected. The principle can be concluded in Eq. (3.1)

$$P + \frac{1}{2}\rho V^2 = constant \tag{3.1}$$

The equation can be further differentiated to Eq.(3.2)

$$dP = -\rho V dV \tag{3.2}$$

Eq. (3.2) is named as Euler's equation. This equation is applicable to an inviscid flow with no body forces involved. It only relates the variation of flow velocity, dV to the change of flow pressure, dP along the streamline.

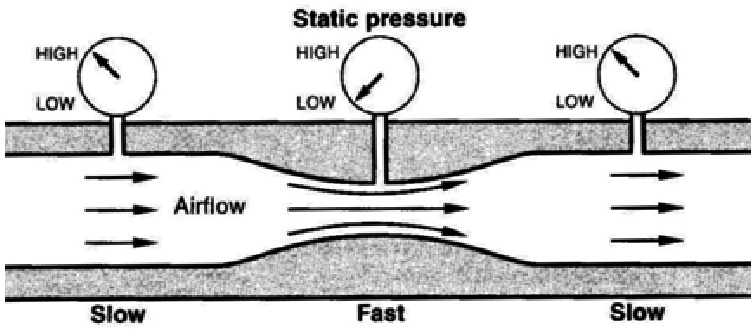

Figure 3.1: Bernoulli's principle in valve shows that lower flow velocity possesses higher static pressure and vice versa (Glogster, 2015).

To study the flow properties between two points in a streamline, Bernoulli's equation, Eq. (3.3) is applied for the calculation, which relates pressure, P_1 and velocity, V_1 at point 1 with pressure, P_2 and velocity, V_2 at point 2.

$$P_1 + \frac{1}{2}\rho {V_1}^2 = P_2 + \frac{1}{2}\rho {V_2}^2 \tag{3.3}$$

The fundamental Bernoulli's equation is only valid for incompressible flows. Incompressible flow is referred to the fluid flow in which the density of fluid, ρ remains constant.

The Bernoulli's principle was derived from the energy conservation principle. It declares that the sum of all energy forms along the flow is the same for all points in the streamline in a steady flow. This implies that the sum of potential energy, kinetic energy and internal energy remains constant throughout the fluid flow. For further explanation, the increasing flow velocity indicates the increasing of dynamic pressure. Hence, the kinetic energy of the flow increases. Simultaneously, the potential energy including static pressure of the flow decreases. The total pressure of the fluid flow is the same at every location in the flow.

3.2 Airfoil Pressure Distribution

An airfoil at a given angle of attack will have its pressure distribution. The pressure distribution describes the pressure which acted at all points around an airfoil. Generally, negative pressure is defined for the upper surface pressure while positive pressure defines lower surface pressure. The flow on upper surface possesses higher velocity, thus create the pressure which lower than ambient pressure, whereas pressure at lower surface is greater than ambient pressure. This phenomenon explained by Bernoulli's principle.

Figure 3.2 shown the pressure distribution of an airfoil at three different angles of attack which are negative, nearly zero and positive angle of attack. As indicated in Figure 3.3, the upper surface possesses lower pressure coefficient compared to lower surface. The stagnation condition occurs at leading edge of the airfoil. At the pressure recovery region, the pressure is gradually increased to the pressure at trailing edge due to adverse pressure gradient phenomenon on airfoil surface.

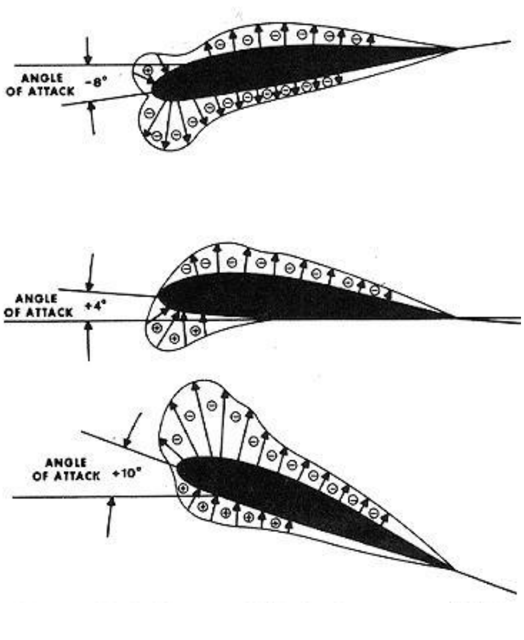

Figure 3.2: Pressure distribution on an airfoil for negative, nearly zero and positive angle of attack (Avstop.com, 2016).

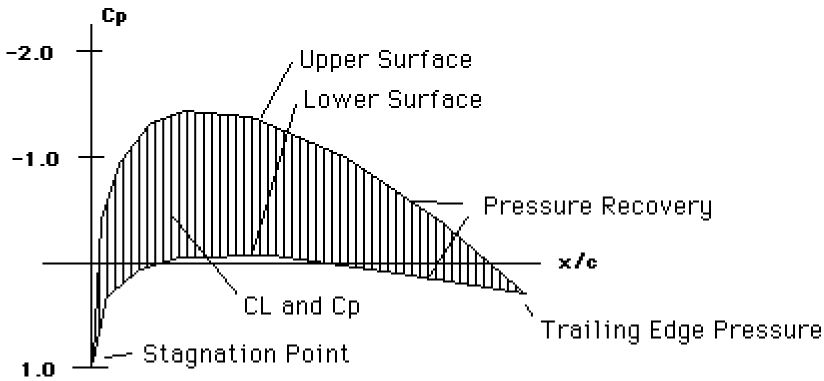

Figure 3.3: Theoretical pressure distribution plot for an airfoil (Kroo, 2007).

3.2.1 Pressure Coefficient

The performance of the airfoil can be determined by measuring the pressure on upper and lower surface of the airfoil. The pressure distribution is expressed by means of pressure coefficient, C_p which is a dimensionless parameter. The pressure coefficient, C_p can be expressed as

$$C_p = \frac{p_i - p_\infty}{q_\infty} \tag{3.4}$$

$$q_\infty = \frac{1}{2}\rho {V_\infty}^2 \tag{3.5}$$

where,

C_p : Pressure Coefficient

q_∞ : Dynamic pressure, Pa

p_i : Pressure at location i, Pa

p_∞ : Static pressure, Pa

ρ : Air density, kg/m^3

V_∞ : Free stream velocity, m/s