COMPARISON BETWEEN FIBER BRAGG GRATINGS AND CONVENTIONAL PRESSURE SENSOR IN SURFACE PRESSURE ANALYSIS OF GENERIC TRANSPORT AIRCRAFT

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DEDICATION

This thesis is wholeheartedly dedicated to my beloved father and mother, who has been my source of inspiration and strength, who continually provide their moral, spiritual, emotional, and financial support.

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ABSTRACT

UTM-LST model is a semi span model of aircraft wing which is scaled as 9% of generic transport. This model is important in investigating aircraft wing aerodynamic performance such as lift, drag and shear forces acting on the wing in various conditions. These forces affect an important aircraft flight parameter which is pressure coefficient, *Cp* and flight performance due to air vortex formation. The established technique for measuring *Cp* is using conventional static pressure sensors embedded into the wing model. This work focuses on measurement of *Cp* and locating air vortex formation on the UTM-LST half model surface. Two techniques, namely, fiber Bragg gratings (FBGs) strain sensor and static pressure sensors were employed for these purposes and measurement were performed inside a low speed wind tunnel. The FBGs strain sensor was placed as close as possible to the pressure sensor taps to allow more accurate comparison of *Cp* measurement between these two techniques. The wind tunnel test was conducted at the wind speed, v in the range of 20 $\mathrm{m\ s^{-1}}$ to 40 $\mathrm{m\ s^{-1}}$ and the angle of attack, α in the range of 0° to 20°. The results revealed that FBGs sensors are capable in measuring *Cp* and to locate the air vortex formation on the wing. The *Cp* values obtained using FBGs were well in agreement with *Cp* values obtained using conventional static pressure sensors except the *Cp* obtained at separation region. The *Cp* measured using FBGs experiences strain due to air pressure from all directions is not only from wind flow but from vortices as well. The *Cp* obtained by pressure sensor is only affected by pressure difference. Thus, *Cp* measured using FBGs is higher than the one measured by pressure sensors. The formation of air vortex using FBGs can then be determined based on the location on wing that has a higher *Cp* from FBGs sensor compared to the one measured using conventional pressure sensors. In conclusion, the FBG strain sensor can be used as an alternative technique to determine *Cp* and to locate air vortex formation.

ABSTRAK

Model UTM-LST adalah model separuh panjang sayap pesawat yang berskala 9% daripada pesawat komersial. Model ini penting untuk mengkaji prestasi aerodinamik sayap pesawat seperti daya angkat, daya seretan dan daya ricihan yang bertindak pada sayap dalam pelbagai keadaan. Daya ini mempengaruhi parameter penerbangan pesawat yang penting iaitu pekali tekanan, *Cp* dan prestasi penerbangan yang disebabkan oleh pembentukan vorteks udara. Teknik yang digunakan untuk mengukur *Cp* adalah sensor tekanan statik konvensional yang telah terbina di dalam model sayap. Kerja ini memberi tumpuan kepada pengukuran *Cp* dan untuk mencari lokasi pembentukan vorteks udara pada permukaan model sayap UTM-LST. Dua teknik iaitu sensor terikan parutan Bragg gentian (FBG) dan sensor tekanan statik telah digunakan untuk tujuan tersebut dan ukuran ini telah dilakukan di dalam terowong angin kelajuan rendah. Sensor terikan FBGs diletakkan sedekat mungkin dengan paip sensor tekanan untuk membolehkan perbandingan lebih tepat bagi pengukuran *Cp* menggunakan kedua-dua teknik ini. Ujian terowong angin dilakukan pada kelajuan angin, v dalam julat 20 m s^{-1} sehingga 40 m s^{-1} dan sudut serang, α dalam julat 0° sehingga 20°. Hasil kajian menunjukkan bahawa sensor FBG mampu mengukur *Cp* dan mencari pembentukan vorteks udara pada sayap. Nilai *Cp* yang diperoleh menggunakan FBG hampir sama dengan nilai *Cp* yang diperoleh menggunakan sensor tekanan statik konvensional kecuali *Cp* yang diperoleh di kawasan pemisahan aliran. Nilai *Cp* yang diukur dengan menggunakan FBG adalah disebabkan tekanan udara yang bertindak dari semua arah dan bukan hanya disebabkan aliran angin, malah juga dari vorteks. Nilai *Cp* yang diperoleh sensor tekanan hanya dipengaruhi oleh perbezaan tekanan. Oleh itu, nilai *Cp* yang diukur menggunakan FBG menjadi lebih tinggi daripada bacaan sensor tekanan. Pembentukan vorteks udara menggunakan FBG boleh ditentukan berdasarkan lokasi pada sayap yang mempunyai nilai *Cp* yang lebih tinggi berbanding dengan *Cp* yang diukur menggunakan sensor tekanan konvensional. Kesimpulannya, sensor FBG boleh digunakan sebagai kaedah alternatif untuk menentukan *Cp* dan untuk mencari pembentukan vorteks udara.

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LIST OF ABBREVIATIONS

PSP	-	Pressure-sensitive paint
DBD	-	Dielectric barrier discharge
FBGs	-	Fiber Bragg Gratings
UTM-LST	-	Universiti Teknologi Malaysia Low Speed Wind Tunnel
CCD	-	Charge-coupled device
PIV	-	Particle Image Velocimetry
UV	-	Ultraviolet
LED	-	Light-emitting diode
PMT	-	Photomultiplier tubes
PD	-	Photodiodes
JAXA	-	Japan Aerospace Exploration Agency
NASA	-	National Aeronautics and Space Administration
TWT1	-	Transonic wind tunnel
PtTFPP	-	Platinum(II) mesotetra(pentafluorolphenyl) porphine
TSP	-	Temperature-sensitive paint
CFD	-	Computational Fluid Dynamics
USA	-	Unite States of America

LIST OF SYMBOLS

Cp	-	Pressure coefficient
v	-	Free stream velocity
α	-	Angle of attack
L	-	Lift
D	-	Drag
R	-	Resultant force
W	-	Weight
M	-	Moment
m	-	Moment coefficient
S	-	Surface area
$\mu\infty$	-	Speed constant
Re	-	Reynold number
P	-	Static pressure at point of interest
P_o	-	Static pressure in free stream
τ	-	Lifetime
I	-	Intensity
K_{SV}	-	Stern-Volmer constant
Q	-	Quencher or partial pressure of oxygen
λ_B	-	Bragg wavelength
n	-	Refractive index
Λ	-	Grating period
$\Delta\lambda$	-	Wavelength shift
λ_o	-	Initial wavelength
p_e	-	Strain-optic coefficient
ε	-	Strain experienced by the grating
α_Λ	-	Thermal expansion coefficient
α_n	-	Thermo-optic coefficient
ΔT	-	Temperature change
x/c	-	Ratio of point of measurement and chord length

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Pressure coefficient, *Cp* is widely used in industry and scientific research to describe the relative pressure of a model. Every point in a fluid flow field has its own unique *Cp* which makes multipoint pressure measurement very important to get the best picture for the flow separation. In aerodynamic studies, analyzing the *Cp* on surface flow measurement helps the researcher and manufacturer to locate the flow separation formation on the aircraft and automotive models. It is very important to improve the designs for optimum flight and cruising performance. In aircraft manufacturing, the surface pressure measurement is crucial for effective and safe handling. The *Cp* can show the pressure distribution along the surface of the model with the help of the pressure sensors.

In aircrafts pressure measurement study, the *Cp* is affected by the wind speed (v), angle of attack (α), and the density of fluid (ρ) (Corda, 2017). The change in these factors will change the aerodynamic flow of the wind around the airfoil which will lead to the change in pressure due to the force exerted by the wind on the surface area of the airfoil. Therefore, the pressure sensor is a crucial instrument in aircraft transportation as it provides information such as the lift force produced when it is moving at certain speed, v at different angle of attack, α during take-off and changing the altitude. The density of fluid is changing as the aircrafts moving at different altitude and climate.

The failure of this sensors can cause fatal crash such happened to Ethiopia Airlines crash on 10th March 2019 and Lion Air 737 on 29th October 2018 (AFP, 2018). The Ethiopia Airlines crash was caused by the anti-stall system activated automatically before the plane crashed near Bishoftu, Ethiopia which killed all 157 people on board (Reuters, 2019). The Lion Air 737 erroneous input from pitching angle sensors caused the plane crashed into the sea of Jakarta and sacrificed 188 life of passengers and crew (AFP, 2018). These incidents caused all airlines grounding the Boeing 737 MAX 8 flight operation. This has risen the awareness to the manufacturers to prioritise the development of sensors before the aerodynamics of the aircraft.

A few sensors such as static pressure sensors and pressure-sensitive paint, (PSP) have been studied in the past to investigate the aerodynamic drag in order to optimize in-flight conditions and improve the flight safety (Corke, Enloe and Wilkinson, 2010). The static pressure sensor is the most common method used in surfaces pressure measurement study because it gives the most accurate measurement (Gregory *et al.*, 2008). On the other hand, PSP method is less precise since it uses intensity of luminescence emitted by excited oxygen molecules (Liu *et al.*, 1997).

For active control mechanism, dielectric barrier discharge (DBD) plasma actuators has been used to reduce the skin friction drag around the model (Segawa *et al.*, 2013). DBD plasma actuator consists of two conductors separated by dielectric materials and use high-voltage power supply to generate plasma. The generated plasma can reduce the net flow separation on a model. The application of the plasma actuators in actual flight is yet to be identified because of the ability to withstand high pressure in various real flight condition.

The use of optical strain sensors using Fiber Bragg Gratings (FBGs) since the beginning of 20th century gains attention among researchers to investigate the feasibility of FBGs in the surface pressure measurement. This is because FBGs can simply be attached to desired location on the model, without modifying the structure of the model. Besides, FBGs is very thin and lightweight making it suitable to be used in surface pressure measurement as it would not disturb the aerodynamics of the flow. Other advantages of FBGs is that they have very high sensitivity, stable spectrum reflectivity, and is not affected by electromagnetic field (Kreuzer, 2006). The air pressure is determined by calculating the Bragg wavelength shift caused by strain exerted on the gratings

This work is carried out to design an array of FBGs strain sensor and investigate the performance of FBGs in measuring *Cp* and to locate the flow separation on aeroplane wing model known as generic Universiti Teknologi Malaysia Low Speed Tunnel (UTM-LST) half-model (Mansor, 2008). The results obtained by FBGs strain sensors are compared to the *Cp* obtained by static pressure sensors known as FKPS 30DP. The outcome of this project can provide an alternative way for *Cp* measurement which is more compatible and convenient.

1.2 Problem Statement

The study of surface control and its effects on aircraft flow separation has been an interesting field for many researchers. The pressure coefficient, *Cp* is the desired parameter being measured in this study. This parameter provides a very clear visual of air pressure distribution on the wing model. Hence, the air separation location can be determined by analyzing the air pressure coefficient. It is necessary to locate the position of the air vortices formation to improve the design of the existing aircraft to enhance its performance.

There are two conventional pressure sensors commonly used in this field, called as static pressure sensor and pressure-sensitive paint. However, the conventional static pressure sensors require a custom-made model which has holes on the body surface to install the pressure tubes to measure the pressure distribution. This means the design of the model must consider the sensor installation. Once the model is made, the position of the hole is fixed, thus pressure measurement is recorded on that position. If the measurement at some other points are required then, it cannot be performed on the same model. This is one of the disadvantages of using static pressure sensor.

Other disadvantage of this sensor is the clogged problem either at the holes or inside the tubes. This problem is identified as icing in aviation where ice is formed around the aircraft surface and leading edge of the wing due to atmospheric condition at high altitude (SKYbrary, 2016). The ice can block the sensor holes and give error pressure reading.

Meanwhile, the pressure-sensitive paint has very complicated and long procedures before the model can be tested as it needs time to paint the model and let it completely dry. This method is limited to a scaled model in order to get accurate pressure distribution photograph (Nakajima *et al.*, 2008). This is due to the reason that illumination light and charge coupled device, (CCD) camera can only covered a small area of model.

As an alternative technique, FBGs strain sensors can be used to measure the pressure on the Generic UTM Half-model. This sensor can be installed and removed without having to embed the sensors permanently as the static pressure sensor technique. The FBGs strain sensor is thin and light thus it can be easily attached on the desired surface without disturbing the aerodynamic of the system.

1.3 Research Objectives

The objectives of this project are:

i. To determine the pressure distribution coefficient, *Cp* of UTM-LST half model at various wind speed and angles using FBGs strain sensor.
ii. To determine the location of the flow separation on the UTM-LST half model based on pressure distribution coefficient, *Cp* using FBGs strain sensor.
iii. To evaluate the performance of FBGs strain sensors in determining *Cp* and to locate flow separation on UTM-LST half-model and compare with static pressure sensors.

1.4 Scope of Study

Two arrays of FBGs with five central wavelengths of 1535.0 nm, 1540.0 nm, 1545.0 nm, 1550.0 nm, and 1555.0 nm are attached on the surface of aircraft model called UTM-LST Half model. The gratings are attached in perpendicular position to the direction of wind to enhance the strain effect on the sensors. The model is placed in Universiti Teknologi Malaysia Low Speed Wind Tunnel (UTM-LST) for testing at the wind speed, v = 20 m s^{-1}, 30 m s^{-1}, and 40 m s^{-1} with the angles of attack, α = 0°, 3°, 6°, 9°, 12°, 15°, 18° and 20°.

The pressure distribution is measured simultaneously using static pressure sensor and the FBGs strain sensors. The spectral response is recorded using interrogator to calculate the Bragg wavelength shift. The data is then compared to the pressure distribution obtained using FKPS 30DP electronic pressure scanner to calculate the pressure coefficient distribution on the aircraft model.

There is a limitation that needed improvement to get a more reliable data for the develop FBGs strain sensor. The first one is the pre-strain of the FBGs grating sensors when attached on the model. Applying pre-strain can increase the sensitivity of the FBGs by supressing the pressure induced by mechanical contraction of the fiber. The second constrain was the invisible tape used to attach the sensors needed to be properly pasted to the model or it will be detached due to high wind speed produced by the turbine.

1.5 Significant of Study

The pressure measurement study is very important in manufacturing and improvising the design of aircraft models. This study can provide an alternative technique in *Cp* measurement which is more convenient and compatible. The *Cp* obtained can be used to determine the flow separation location thus provides useful information to improvise the design of the wing model for optimum fight condition and increase the load of the flight. FBGs strain sensor can be easily used at any model without any modification that can affect the aerodynamics of the system. Hence, the design of automotive vehicles especially aircraft can be improved without a new model. This method can overcome the clogged tube problem in static pressure technique due to the formation of ice at higher altitude (SKYbrary, 2016).

1.6 Thesis Outlines

Chapter 2 gives an overview on the aerodynamics characteristics of an airfoil during flight, flow separation, and pressure coefficient in terms of definition and the factors that affect them. The conventional pressure sensors were also presented in this chapter to show the working principle, advantages and disadvantages of each pressure sensor. An overview of the fiber Bragg grating sensors in term of structure, working principle, and applications were mentioned. The properties of wing model and wind tunnel test section were described in this chapter.

Chapter 3 is the research methodology of this study. A new design of FBGs strain sensors and the properties of the sensors were presented. All the components and structure of the strain sensors were reported in detail. The experimental setup such as angle of attack and wind speed to achieve the objectives of this study to locate air vortex formation and to evaluate the performance of the FBGs strain sensors were clearly demonstrated. Also included in this chapter the calibration of the FBGs sensors and the calculation of *Cp* for the sensor.

Chapter 4 reveals the experimental results of all the tests conducted in chapter 3. The *Cp* measured by the FBGs strain sensor did not differ much from the *Cp* measured by the conventional pressure sensor. However, at low angle, the FBGs strain sensor will experienced more drag force at the leading edge of the model. The FBGs strain sensor measured very high *Cp* at certain point and angle of attack along the separation region compared to the pressure sensor. The performance of FBGs strain sensor for surface pressure measurement and locating air vortex formation was discussed.

Chapter 5 concluded that the objectives of this study are achieved. Future work to improve the FBGs strain sensors in term of sensitivity and reliability for surface pressure measurement is suggested. Two suggestions were given for the areas can be further investigated to improve the performance of the sensors.

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