



UNIVERSITI PUTRA MALAYSIA

**LONGITUDINAL AERODYNAMIC CHARACTERISTICS OF AN
AIRCRAFT MODEL WITH AND WITHOUT WINGLET**

MD. ALTAB HOSSAIN.

FK 2005 19



**LONGITUDINAL AERODYNAMIC CHARACTERISTICS OF AN AIRCRAFT
MODEL WITH AND WITHOUT WINGLET**

By

MD. ALTAB HOSSAIN

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Master of Science.**

October 2005



DEDICATION

Dedicate this thesis

To his teachers;

To his parents Md. Golbar Hossain and Mrs. Aleya Khatoon

And

To the memory of his Late Grandfather who had devoted his love and guiding of the family



Abstract of thesis presented to Senate of the Universiti Putra Malaysia in fulfilment
of the requirements for the degree of Master of Science

**LONGITUDINAL AERODYNAMIC CHARACTERISTICS OF AN AIRCRAFT
MODEL WITH AND WITHOUT WINGLET**

By

MD. ALTAB HOSSAIN

October 2005

Chairman: Associate Professor Prithvi Raj Arora, PhD

Faculty: Engineering

The measurement of aerodynamic forces and moments acting on an aircraft model is important for the development of wind tunnel measurement technology. The primary purpose of wind tunnel measurements over the model for the forces and moments is to predict the performance of the full-scale vehicle. Force measurement techniques in wind tunnel testing are necessary for determining a variety of aerodynamic performance parameters. For three-dimensional aircraft models, forces and moments are usually measured directly using a balance system. The balance mechanically separates the total aerodynamic load on a model into its six aerodynamic components. Two fundamental types of balances, external and internal balances, are used today. External balances carry the loads outside the tunnel before they are measured and internal balances which fit in the model and are arranged to send data out through electrical wires.



In this research work, six-component external balance is commissioned and the calibration has been thoroughly checked and the detailed procedure of measurement of aerodynamic forces is recommended. A set of winglet has been designed for the existing aircraft model at the Aerodynamics laboratory of the Aerospace Engineering Department, UPM. Further the aerodynamic forces are measured on the aircraft model having a rectangular wing with and without winglet attached to the model. Tests have been carried out on the aircraft model with and without winglet at the Reynolds numbers 170,000, 210,000 and 250,000. The experimental results show that lift curve slope increases by 1-6% with the addition of certain winglet configurations and at the same time the drag decreases by 20-28% as compared to those for the aircraft model without winglet for the maximum Reynolds number considered in the present study.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi sebahagian keperluan untuk ijazah Master Sains

**PENYELIDIKAN TERHADAP CIRI-CIRI AERODINAMIK PADA ARAH
MENDATAR KE ATAS MODEL PESAWAT BER “WINGLET” DAN
TANPA “WINGLET”**

Oleh

MD. ALTAB HOSSAIN

Oktober 2005

Pengerusi: Profesor Madya Prithvi Raj Arora, PhD

Fakulti: Kejuruteraan

Pengukuran daya dan momen aerodinamik yang bertindak ke atas sesebuah model pesawat adalah penting dalam pembangunan teknologi pengukuran untuk bagi terowong angin. Tujuan utama pengukuran daya dan momen tersebut terhadap model ialah untuk meramal prestasi saiz sebenar kenderaan yang diuji. Teknik pengukuran adalah perlu dalam menentukan pelbagai parameter prestasi aerodinamik. Untuk model sebuah pesawat tiga-dimensi daya dan momen diukur terus menggunakan sebuah sistemimbangan. Sistem,imbangan memisahkan daya paduan keatas models kepada enam komponen aerodinamik. Dua jenis azas timbangan yang digunakan setakat ini iaitu timbangan luar dan timbangan dalam. Timbangan dalam menahan beban diluar terowong sebelum diukur dan timbangan dalam yang mana terpasang di dalam model dan diatur untuk mengirim data melalui wayar electrik.

Dalam kajian ini, enam komponenimbangan luaran diuji dan tentu ukur diperiksa dan prosedur terperinci mengenai pengukuran daya-daya aerodinamik dicadangkan. Satu set “winglet” telah direka untuk model pesawat sedia ada di makmal Aerodinamik Jabatan Kejuruteraan Aeroangkasa, UPM. Seterusnya, daya-daya aerodinamik terhadap model pesawat yang mempunyai sayap empat segi tepat dengan “winglet” dan tanpa “winglet” telah dianalise. Ujian telah dijalankan ke atas model pesawat dengan “winglet” dan tanpa “winglet” pada nombor “Reynolds” 170000, 210000 dan 250000. Keputusan eksperimen menunjukkan bahawa kecerunan lengkung daya angkat meningkat 1-6% dengan menggunakan konfigurasi “winglet” tertentu dan dalam masa yang sama daya seret berkurangan sebanyak 20-28% dengan membandingkan keputusan model pesawat tanpa “winglet” untuk nombor “Reynolds” maksimum yang dipertimbangkan dalam kajian ini.



ACKNOWLEDGEMENTS

First of all my thanks and gratitude to Allah for the completion of this research successfully. I would like to express my heart-felt thanks and sincere gratitude to my supervisor Associate Professor Dr. Prithvi Raj Arora and the members of the supervisory committee, Dr. Prasetyo Edi, Dr. Abdul Aziz Jaafar and Associate Professor Dr. Thamir Sabir Younis. Their doors were always open for me to get help and suggestions whenever needed. It is beyond doubt that without their assistance and kind support, it was impossible for me to complete this research work.

I am grateful to Dr. Ahmad Samsuri Mokhtar, Head of the Aerospace Department, Faculty of Engineering for his encouragement and support to complete this research work. My appreciation also goes to all of my teachers especially to Prof. Ir. Dr. ShahNor Basri, Associate Professor Mohd. Ramly Mohd. Ajir, Dr. El-Sadiq Mahdi, Dr. Mohammad Salim, Lt. Kol. (B) Mohs. Tarmizi Ahmad, and En. Mohammad Nizam Filipski Abdullah for their support and co-operation.

I acknowledge the Ministry of Science, Technology and Environment (MOSTE), Malaysia and to the Universiti Putra Malaysia (UPM) for the research grants to carry out the research work. I am also thankful to Mr. Rofiee Mat, Mr. Daeng, Mr. Ahmad Saifol Abu Samah, Mr. Irfan, Mr. Thariq, Mr. Azmin, Mr. Catur, Mr. Suresh Jakob, Mr. Fuaad Hasan, and Mr. Noorfaizal for their all kinds of technical advices and kind help.



I feel proud to express that all of my family members including my parents, grandmother, brothers, uncles and aunts gave me help, guidance and inspiration through out this work. Their sacrifice and love made this thesis a great success in my carrier.

Last but not the least, my appreciation and thanks to all around my surroundings especially to Dr. Zahangir Alam and Mrs. Zahangir, Dr. Md. Liakot Ali, Dr. Md. Abul Hossen Mollah, Dr. Md. Aminul Haque, Mr. Aatur Rahman, Mr. Ahsan Ali, Mr. Anayet Karim and Mrs. Anayet, Mr. Jakir Hossen, Mr. A.K.M. Parvez Iqbal, Mr. Mannan Sarkar, my cousin Dr. Joynul Abedin, my friends Md. Shafiquzzaman Siddiquee, Hena, Md. Sohel Mustafiz, Mrs. Shamima Kabir, Md. Ibrahim Mehedi, Saadat, Obayed and all my country people in UPM, for their help and co-operation during my struggle in the MSc. pursuit.



TABLE OF CONTENTS

	Pages
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL	ix
DECLARATION	xi
LIST OF TABLES	xiv
LIST OF FIGURES	xvi
LIST OF ABBREVIATIONS	xviii
LIST OF SYMBOLS	xix
CHAPTER	
1 INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	3
1.3 Objectives of the Study	4
1.4 Organization of the Thesis	4
2 LITERATURE REVIEW	
2.1 Background	6
2.2 Induced drag and winglets	7
2.2.1 Coefficient of Induced Drag	9
2.2.2 Reduction of Induced Drag	11
2.3 Application of Winglets	11
2.3.1 Winglet for Sailplane	14
2.3.2 Winglet for Roadable Aircraft	16
2.3.3 Winglet for Hydrodynamic Surfaces	18
2.3.4 Winglet for Wind Turbines	18
2.3.5 Winglet for Flat Plate Model	19
2.4 Wing Tip Devices	19
2.4.1 Hoerner Tips	20
2.4.2 Wing Endplates	21
2.4.3 The Winglet	21
2.5 Wing tip modifications for performance improvement	22
2.5.1 Background	22
2.5.2 Conventional or Blended Winglet	23
2.5.3 Spiroid Technology	24
2.5.4 Wing with Multiple Winglets	25
2.6 Summary of the Literature Review	27
2.7 Conclusions of the Literature Review	28



3	METHODOLOGY	
3.1	Synopsis	29
3.2	Model Details	29
3.2.1	Wing Details	29
3.2.2	Winglet Design	30
3.2.3	Drawing of the Winglet	31
3.2.4	Description of Six-Component External Balance	32
3.3	Calibration of External Balance	33
3.3.1	Procedure of Calibration	33
3.4	Wind Tunnel Testing	40
3.4.1	Description of Wind Tunnel	40
3.4.2	Basic Components of Low Subsonic Wind Tunnel	40
3.4.2.1	Test Section	41
3.4.2.2	Contraction Cone	42
3.4.2.3	Settling Chamber and Screens	42
3.4.2.4	Diffuser	43
3.4.2.5	Driving Unit	44
3.4.2.6	Specification of the Wind Tunnel	44
3.4.3	Test Section Flow Calibration	45
3.4.3.1	Free Stream Velocity Calibration	45
3.4.3.2	Flow Uniformity	52
3.4.4	Starting Procedure	55
3.4.5	Testing Procedure	56
3.4.6	Specimen Calculation	56
3.4.7	Testing of the Aircraft Model with Elliptical and Circular Winglet	61
3.4.8	Verification of Wind Tunnel Measurement	62
3.4.8.1	Specimen Calculation	63
3.5	Project Structure Flow Chart	69
4	RESULTS AND DISCUSSIONS	
4.1	Results and Discussions	70
4.1.1	Coefficient of Lift	70
4.1.2	Coefficient of Drag	84
4.1.3	Coefficient of Pitching Moment	88
4.1.4	Lift/Drag Ratio	92
4.2	Effect of Winglet Geometry	95
4.2.1	Coefficient of Lift	95
4.2.2	Coefficient of Drag	97
4.2.3	Lift/Drag Ratio	98
5	CONCLUSIONS AND RECOMMENDATIONS	
5.1	Conclusions	102
5.2	Recommendations for Future Research Works	104
	REFERENCES	105
	APPENDICES	109
	BIODATA OF THE AUTHOR	128



LIST OF TABLES

Table	Pages
3.1: Load locations at different steps	34
3.2: Equivalent forces and moments for different load conditions	35
3.3: Sensor readings corresponding to different load conditions	35
3.4: Inverse of coefficient matrix (Calibration Matrix)	38
3.5: Calibration matrix supplied with six component external balance	39
3.6: Percentage of Error	39
3.7: Wind tunnel external balance software velocity (m/s) for corresponding Hz	46
3.8: Digital manometer reading (Dynamic pressure) for corresponding Hz	47
3.9: Digital manometer reading (Velocity) for corresponding Hz	48
3.10: Manometer tube reading (Dynamic pressure) for corresponding Hz	49
3.11: Manometer tube reading (Velocity) for corresponding Hz	50
3.12: Wind tunnel external balance software velocity and Digital manometer velocity for corresponding Hz	51
3.13: Dynamic pressure reading (Pa) at different locations of YZ-plane	54
3.14: Dynamic pressure variations from the mean (%) at different locations of YZ-plane	54
3.15: Free stream velocity and corresponding Reynolds and Mach number	58
3.16: Winglet Configurations	61
3.17: Drag force for corresponding free stream velocity	62
3.18: Free stream velocity and corresponding Reynolds and Mach number	64
3.19: Calculated drag coefficients and Reynolds number	66
3.20: Experimental drag coefficients data and Reynolds number	67
4.1: Aerodynamic forces acting on the aircraft model without winglet	71



4.2: Aerodynamic forces acting on the aircraft model with elliptical winglet of configuration 1	72
4.3: Aerodynamic forces acting on the aircraft model with elliptical winglet of configuration 2	73
4.4: Aerodynamic forces acting on the aircraft model with circular winglet of configuration 1	74
4.5: Aerodynamic forces acting on the aircraft model with circular winglet of configuration 2	75
4.6: Lift coefficient, Drag coefficient, and Pitching moment coefficient data for the aircraft model without winglet	76
4.7: Lift coefficient, Drag coefficient, and Pitching moment coefficient data for the aircraft model with elliptical winglet of configuration 1	77
4.8: Lift coefficient, Drag coefficient, and Pitching moment coefficient data for the aircraft model with elliptical winglet of configuration 2	78
4.9: Lift coefficient, Drag coefficient, and Pitching moment coefficient data for the aircraft model with circular winglet of configuration 1	79
4.10: Lift coefficient, Drag coefficient, and Pitching moment coefficient data for the aircraft model with circular winglet of configuration 2	80
4.11: Lift coefficients experimental data	82
4.12: Drag coefficients experimental data	86
4.13: Pitching moment coefficients experimental data	90
4.14: Lift/Drag Ratio experimental data	95
4.15: Lift curve slope (per radian) for all the configurations	97

LIST OF FIGURES

Figures	Pages
1.1 Airplane Configuration with Winglets	2
2.1 KC-135 Winglet Flight Tests at Dryden Flight Research Centre	8
2.2 Formation of Wingtip Vortices	9
2.3 Induced Drag on the Aerofoil	10
2.4 Typical Winglet Application	13
2.5 View of the Pegasus in flight	18
2.6 Hoerner Tips and Round Tips before Testing	21
2.7 Conventional and Blended Winglet	24
3.1 Geometric Characteristics of the Wing Planform	29
3.2 NACA 65 ₃ -218 Aerofoil	30
3.3 Full Model Balance Assembly under Test Section	33
3.4 TOP view of Calibration Rig	34
3.5 Open Loop Low Speed Wind Tunnel (OLWT-1000)	41
3.6: Free stream velocity curves.	50
3.7: Free stream velocity curves for calibration	52
3.8: Schematic view of wind tunnel test section	53
3.9: Dynamic pressure variations from the mean (%) in the test section	55
3.10: Drag Coefficients for sphere as a function of the Reynolds number	68
4.1 Lift Coefficients for the Aircraft Model	83
4.2 Drag Coefficients for the Aircraft Model	87
4.3 Pitching Moment Coefficients for the Aircraft Model	91



4.4	Lift/Drag Ratio for the Aircraft Model	93
4.5	Lift Coefficient for the Aircraft Model	96
4.6	Drag Coefficient for the Aircraft Model	98
4.7	Lift/Drag ratio for the Aircraft Model	99



ABBREVIATIONS

AFFDL	Air Force Flight Dynamics Laboratory
BBJ	Boeing Business Jet
CNC	Computer Numerically Controlled
DOC	Direct Operating Cost
LaRC	Langely Research Center
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
OLWT	Open Loop Wind Tunnel
PSU	Pennsylvania State University
RPM	Revolutions Per Minute



LIST OF SYMBOLS

b	Wing span
c	Chord length
α	Angle-of-attack
D	Drag force
D_i	Induced drag
L	Lift force
M	Pitching moment
N	Newton
Nm	Newton meter
ρ_∞	Air density
S	Plan surface or reference area
AR	Aspect Ratio
e	Efficiency factor
δ	Constant
μ_∞	Viscosity of air
T	Ambient temperature
K	Kelvin
V_∞	Free stream velocity
Re	Reynolds number
M_∞	Mach Number
a_∞	Speed of Sound
R	Gas constant



q_{∞}	Dynamic pressure
C_D	Drag coefficient
C_{Di}	Coefficient of Induced drag
C_L	Lift coefficient
C_M	Pitching moment coefficient
L/\bar{D}	Lift/Drag
C1	Load No. 1
C2	Load No. 2
C3	Load No. 3
C4	Load No. 4
C5	Load No. 5
C6	Load No. 6
L_i	Signal Matrix
K_{ij}	Coefficient Matrix
F_i	Load Matrix

CHAPTER 1

INTRODUCTION

1.1 Background

One of the primary barriers limiting the performance of aircraft is the drag that the aircraft produces. This drag stems from the vortices shed by an aircraft's wings, which causes the local relative wind downward (an effect known as downwash) and generate a component of the local lift force in the direction of the free stream. The strength of this induced drag is proportional to the spacing and radii of these vortices. By designing wings, which force the vortices farther apart and at the same time create vortices with larger core radii, it may significantly reduce the amount of drag the aircraft induces. Airplanes which experience less drag require less power and therefore less fuel to fly an arbitrary distance, thus making flight, commercial, more efficient and less costly. One promising drag reduction device is the winglet. For a number of years many investigations have been carried out to prove the possible benefits of modifying wing tip flow. Tip devices have become a popular technique to increase the aerodynamic performances of lifting wings. The idea behind all the devices described is to diffuse the strong vortices released at the tip and optimise the span wise lift distribution, while maintaining the additional moments on the wing within certain limits (Filippone, 2004). Winglets have increasingly become a popular method of altering the trailing tip vortex system from an aircraft wing and thus improve the aircraft performance. A winglet is a device used to improve the efficiency of aircraft by lowering the lift-induced drag caused by wingtip vortices. A winglet provides an innovative method of achieving the

vortex arrangement described above. The concept involves constructing wings whose tips are small extension in the form of a smaller aerofoil section placed at any angle, as shown in Figure 1.1.

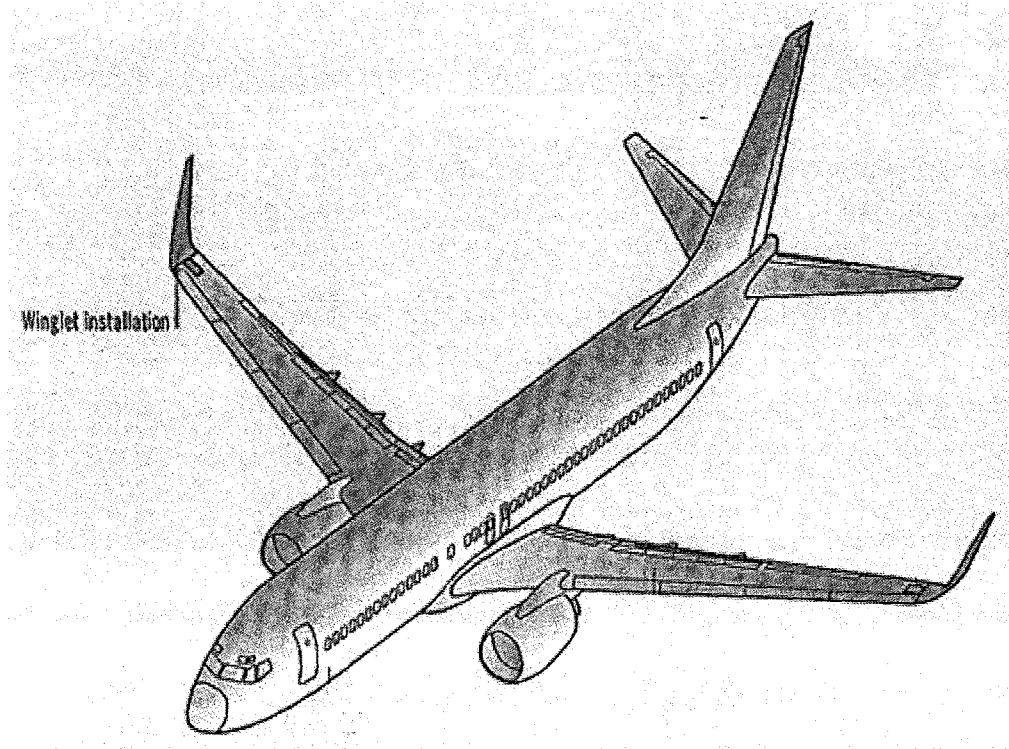


Figure 1.1: Airplane Configuration with Winglets (Boeing Commercial Airplanes, Washington).

Because the vortices shed by the wing are strongest at the tips of the wing, the addition of wing tip surfaces can reduce and diffuse the strength of these vortices, thus reducing the overall vortex drag of the aircraft (Asselin, 1997). Two pairs of winglets are used with the aircraft model existing in Aerodynamics Laboratory of Aerospace Engineering Department, Universiti Putra Malaysia. The longitudinal aerodynamic characteristics of aircraft model with two-winglet configuration have been the subject of this research work.

1.2 Problem Statement

The airfoil is the heart of an airplane it affects the cruise speed, takeoff and landing distances, stall speed, handling qualities (specially near the stall), and overall aerodynamic efficiency during all phases of flight. When wing is generating lift, it has a reduced pressure on the upper surface and an increased pressure on the lower surface. For a wing of finite span, the air on the upper surface flows inward and air below the under-surface flows outward. For this reason there is a continual spilling of the air round the wing tip from the bottom surface of the wing to the upper surface. These two airflows meet at the trailing edge and cause wing-tip vortices. If there is a wing of infinite aspect ratio, the air flows over the wing surface without any inward or outward deflection, and therefore no wing-tip vortices, no induced drag. But such a thing is impossible in practical flight, and for this reason the effective aspect ratio is increased as large as is practicable by using winglet. The extension of wingspan permit the lowering of drag but this comes at a cost of increasing the strength of the wing and hence its weight. This establishes the need for the winglet. Winglets work by increasing the aspect ratio of a wing without adding greatly to the structural stress and hence necessary weight of its structure.

The small extension at the wing tip is called winglet and is placed at any angle to the existing wing surface so that the rotating vortex flow at the wing tip creates a lift force on the winglet that has a forward component. This forward component of the lift force reduces the total wing drag. The idea behind the winglet is to produce a flow field that interacts with that of the main wing to reduce the amount of span

wise flow. That is, the span wise induced velocities from the winglet oppose and thereby cancel those generated by the main wing.

The purpose of this investigation is to study the behaviour of an added winglet of varied geometries to a NACA 65-3-218 rectangular wing as a part of an existing aircraft model.

1.3 Objectives of the study

The main objectives of this research work are

1. To compare the calibration matrix with calibration matrix provided with the six-component external balance as supplied by the manufacturer.
2. To design and fabricate a set of winglet for the existing aircraft model at the Aerodynamics Laboratory of the Aerospace Engineering Department, UPM.
3. To measure the lift and drag forces and pitching moment of the aircraft model having a rectangular wing with and without winglet attached to the model by using six-component external balance at the Aerodynamics Laboratory of the Aerospace Engineering Department, UPM.
4. To compare the experimental lift force, drag force and pitching moment for the modified wing of an existing aircraft model with an elliptical and a circular winglets of given aspect ratio with the results obtained through the unmodified aircraft model.

1.4 Organisation of the Thesis

The dissertation is divided into five chapters. In chapter one, the requirements of winglet in the Aerospace industry for the aircraft model are discussed. This chapter