PRELIMINARY STABILITY ESTIMATION AND ANALYSIS OF AEROMECH I UAV USING DATCOM SOFTWARE

AZIZUL BIN ABDULLAH

UNIVERSITI SAINS MALAYSIA

2012

PRELIMINARY STABILITY ESTIMATION AND ANALYSIS OF AEROMECH I UAV USING DATCOM SOFTWARE

By

AZIZUL BIN ABDULLAH

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

UNIVERSITI SAINS MALAYSIA

June 2012

ACKNOWLEDGEMENT

Firstly, Alhamdulillah, all praises to Allah the almighty, for enabling me to finish my master project, as I have been blessed with good health and peaceful mind while doing this project. Next, I would like to express my deepest gratitude to my supervisor Cik Nurulasikin Mohd Suhadis, for her guidance, insight and motivation. I would also like to thank Dipl. Ing. Endri Rachman for his advises and sharing the knowledge with me to solve my problems during this research. To my friends, Azlila Zakaria, Aizam Shahroni Mohd Arshad, Mohd Amir Wahab, Khairul Ikhsan Yahaya, Mohammed Zubair, Fauzi Hussin, Yu Kwok Hwa, and others, thanks a lot for their valuable comments, support and sharing the knowledge.

I am gratefully acknowledging the assistance of everybody who helped me directly and indirectly in the execution of this research, especially the Institute of Postgraduate Studies for providing me funding and the School of Aerospace Engineering for providing me facilities and proper equipments. Last but not the least; I am highly grateful to my beloved mother, Aishah binti Zakaria, Dr. Maznah binti Ismail, and my family members, for their unlimited support, encouragement and patience.

TABLE OF CONTENTS

CHAPTER 3-METHODOLOGY

CHAPTER 4-THEORY OF DATCOM SOFTWARE

CHAPTER 5-RESULTS AND DISCUSSION

CHAPTER 6-CONCLUSION AND FUTURE WORKS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Roman symbols

A	wing aspect ratio
b	wing span
B	compressible sweep correction factor
c	chord
k	ratio of airfoil lift curve slope
l	reference length
S	wing planform area
W	aircraft weight

Greek symbols

α	angle of attack
β	sideslip angle
γ	flight path angle
Γ	dihedral angle
δ_f	flap deflection angle
Δc_l	increment airfoil lift coefficient due to flaps
ΔC_L	increment aircraft lift coefficient due to flaps
Δc_m	increment airfoil pitching moment coefficient due to flaps
ΔC_m	increment aircraft pitching moment coefficient due to flaps
$\Delta \bar{x}_{ac,f}$	shift in aerodynamic center
ε	downwash angle at the horizontal tail
ε_t	wing twist angle
$\Lambda_{\mathrm{c/2}}$	semi chord sweep angle
$\Lambda_{\mathrm{c/4}}$	quarter chord sweep angle
Λ_{LE}	Leading edge sweep angle
λ	taper ratio
μ	coefficient of viscosity for air
ρ	air density

Abbreviations

AATD	Aviation Applied Technology
ADAS	Aircraft Data Acquisition System
AFRL/MN	Munitions Directorate of the Air Force Research Laboratory
APAS	Aerodynamic Preliminary Analysis System
ASRB	Airworthiness and Safety Review Board
BWD	Blended Wing Body
CAD	Computer Aided
CARDC	China Aerodynamic Research and Development Center
CFD	Computational Fluid Dynamics
COA	Certificate of Authority
CPU	Central Processing Unit
CSM	Computational Structural Mechanics
DATCOM	Data Compendium
FAA	Federal Aviation Administration
FEM	Finite Element Method
GPS	Global Positioning System
GSC	Ground Control Station
HILS	Hardware In the Loop Simulation
I/O	Input and Output
IMU	Inertial measurement unit
ISM	Institute of Fluid Mechanics
KARI	Korea Aerospace Research Institute
LSWT	Low Speed Wind Tunnel
MAC	Mean Aerodynamic Chord
MATLAB	Matrix Laboratory
MAV	Micro Air Vehicle
MDO	Multidisciplinary Design Optimization
NACA	(U.S) National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
PWM	Pulse Width Modulation
RC	Remote Control
RHC	Receding Horizon Control

RSTA	Reconnaissance, Surveillance, Target Acquisition
SUAV	Small Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
USM	Universiti Sains Malaysia
WB	Wing Body

ANGGARAN DAN ANALISA KESTABILAN UAV AEROMECH I DI PERINGKAT AWAL REKA BENTUK PESAWAT MENGGUNAKAN PERISIAN DATCOM

ABSTRAK

Kestabilan adalah salah satu aspek yang menyumbang kepada prestasi penerbangan pesawat. Kaedah yang selalu digunakan seperti ujian terowong angin, ujian penerbangan, dan pengkomputeran dinamik bendalir (CFD) digunakan untuk membuat anggaran dan analisa kestabilan semasa proses reka bentuk pesawat. Kaedah-kaedah ini memakan masa yang lama dan mahal kerana ia tidak boleh menentukan pekali kestabilan secara terus.

Oleh itu, sebagai salah satu kaedah alternatif yang berkesan, perisian DATCOM telah digunakan dalam kajian ini, untuk menganggar pekali aerodinamik dan menganalisa kestabilan statik dan dinamik di peringkat awal reka bentuk pesawat kecil tanpa pemandu, UAV AEROMECH I yang dibangunkan oleh Pusat Pengajian Kejuruteraan Aeroangkasa, Universiti Sains Malaysia. Berbeza dengan kaedah konvensional, DATCOM dapat menganggarkan pekali kestabilan statik dan dinamik secara langsung.

Untuk menjana pekali kestabilan UAV AEROMECH I yang diingini melalui DATCOM, siri nama senarai pembolehubah seperti keadaan penerbangan; luas dan panjang sayap; parameter sintesis untuk konfigurasi asas pesawat; geometri asas badan pesawat; data geometri untuk permukaan aerodinamik; data ciri-ciri permukaan aerodinamik; dan kad kes kawalan untuk spesikasi pengguna, telah dihasilkan dalam bentuk kod pengaturcaraan computer.

Keputusan kajian kes daripada perisian DATCOM telah disahkan melalui perbandingannya dengan keputusan dari kaedah semi-empirik dan nilai kestabilan umum bagi pesawat. Anggaran dan analisa kestabilan dengan peratusan kesalahan yang boleh diterima telah dibuat untuk semua nilai kestabilan. Anggaran dan analisa menunjukkan UAV AEROMECH I mempunyai kestabilan yang sesuai diperingkat awal reka bentuk. Keputusan kajian juga membuktikan bahawa DATCOM memiliki kemampuan untuk menganalisa kestabilan UAV yang kecil.

PRELIMINARY STABILITY ESTIMATION AND ANALYSIS OF AEROMECH I UAV USING DATCOM SOFTWARE

ABSTRACT

Stability is one aspect of the aircraft performance. Conventional methods such as wind tunnel test, flight test and Computational Fluid Dynamics (CFD) are used for the estimation and analysis of the stability during aircraft design process. Those methods are time consuming and expensive because they cannot determine the stability coefficients directly.

Thus, as one of the promising alternative methods, the DATCOM software was employed in the present study, in order to estimate the aerodynamic coefficients and analyze the static and dynamic stabilities at the preliminary design stage of a small Unmanned Aerial Vehicle, UAV AEROMECH I which was developed at the School of Aerospace Engineering, Universiti Sains Malaysia. Unlike the conventional methods, the DATCOM facilitated direct estimation of the static and dynamic stability coefficients.

In order to generate the desired stability coefficients of UAV AEROMECH I through the DATCOM, the series of name-list statement listing input variables such as flight condition; the reference area and the length of the wing; the basic configuration synthesis parameters; the basic body geometry parameters; the input data for the aerodynamic surface planforms; the aerodynamic characteristics of the planform surfaces; and the case control card for user specification, were created in the source code.

The results obtained from the DATCOM software were verified by comparing with the results from the semi-empirical method and the typical stability values of

aircraft. Validation and accuracy of the stability with acceptable percentages of errors were made for all of the stability values. The results showed that the UAV AEROMECH I has the reliable stability in the early design stage. The results also proved that DATCOM has the capability for analyzing the stability of small UAV based on the comparison of results that mention before.

CHAPTER ONE

INTRODUCTION

1.1 Overview

Recently, most of the developed countries are trying to develop Unmanned Aerial Vehicle (UAV) due to its proven abilities and capabilities in the military and civilian reconnaissance (Howard and Kaminer, 1995). For making the UAV compatible to do their task it is equipped with the surveillance system such as a full suite of sensor like Global Positioning System (GPS), inertial measurement units, laser range finders and computer vision. Example of UAV that is equipped with such systems is General Atomics' Predator. It carries out the tasks such as reconnaissance and target acquisition (Oh and Green, 2005).

The UAVs are used for wide missions, and according to the mission requirement, they are designed in different performance levels and various sizes. There are four types of UAV that can be indentified based on their size, such as large, medium, small, and micro. The differences among these types are illustrated in Figure1.1.

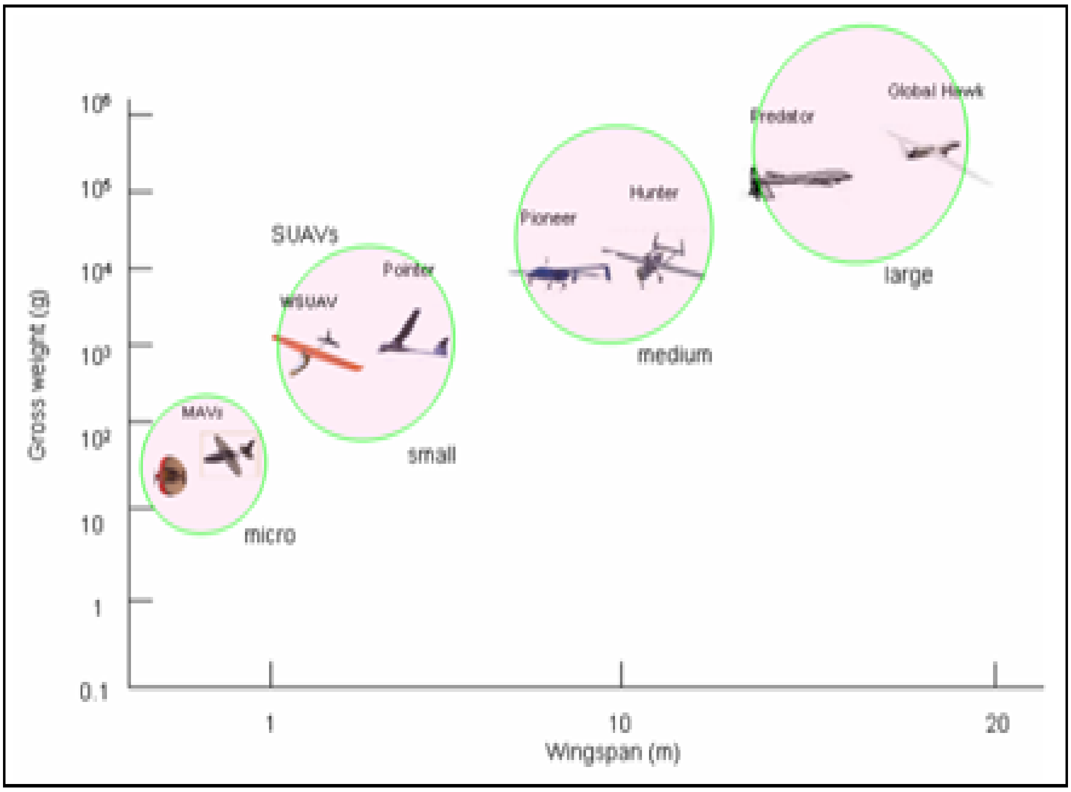

Figure 1.1 Groups of UAVs based on its sizes and weights (Landolfo, 2008)

Generally, the large UAVs have higher speed, long endurance, higher maximum altitude, and carry more payloads that make them more functionally capable. Examples of large UAV are Predator B (20m wingspan) and Global Hawk (35m wingspan) (Cheng, 2007). The Predator has a capability to operate safely from halfway across the world and can give a good view for the operators during flight (Sullivan, 2006); Global Hawk also has the same capability with the Predator. They are capable of flying 24 hours, which makes them more advantageous compared with manned aircraft that needs refuel often and land to change crew (Peck, 2000).

The medium size UAV is commonly used for tactical military missions such as RQ-2A Pioneer (5.1m wingspan) that has outstanding performance in reconnaissance, surveillance, target acquisition (RSTA), NAVAL gunfire support, and battlefield management platform. The RQ-2A Pioneer system received extensive acclaim for its effectiveness in mission by US Army, Navy, and Marine Corps commander (Cook, 2006). Most UAVs in this group do not need the runway because they are launched by the pneumatic launcher or rocket assists. For landing, they use a parachute or recover from short runway with arresting gear (Office of the Secretary of Defence, 2005).

Micro air vehicle (MAV) is defined as miniature aircraft that has less than one foot wingspan. The challenges in the design of MAVs are to ensure that, the structure of the body is light in weight and strong, they consume low power, and possess lightweight autopilot. Moreover, they must be intuitive and user-friendly, with increased autonomy, including path planning, trajectory generation, and tracking algorithms. One of the most popular MAVs is BATCAM that was developed by the Munitions Directorate of the Air Force Research Laboratory (AFRL/MN). This UAV has the potential to monitoring of confined area owing to its smaller size (Beard et al., 2005).

Increasing success of UAV in military and civil reconnaissance inspired not only military and companies but also university researchers to explore further on UAV. The universities have more interest in small UAV (SUAV) because they are "less expensive and less dangerous" (Jang and Liccardo, 2006). One example of SUAV that is relatively inexpensive compared to mid or large UAVs is Aero Vironment Pointer. When it was released in 1986, a package of two UAV and ground station only cost $100,000. Besides that, SUAV can find the threat before it even gets closer and prevents the troops get from harm's way (O'Connor, 2007).

A few of the universities that make research and development in UAV are, Georgia Institute of Technology, University of Sydney, and Universiti Sains

Malaysia. The Georgia Institute of Technology conducts the research on the system of UAV Yamaha R-Max (Johnson et al., 2004). The system of UAV was tested by using Hardware-In-The-Loop (HILS) simulation and flight test. The benefits of their research were, increasing safety during the operation of UAV, the detection of errors before flight testing, and the effective use of flight test data.

The UAV development was started at the University of Sydney since 1988 (Wong, 2006). This process of development was initiated due to the requirement for a dynamic flight test facility to develop various dynamic devices on the laminar flow wing. This initiative, consequently, led the formation of a UAV Research Group with members working on a wide variety of UAV related research projects. A few UAV projects that have been done at the University of Sydney are KCEXP-series UAVs, Ariel UAV, and Brumby UAV. All the UAV design and development at University of Sydney have led to numerous operational flight platforms. These platforms, in turn, have been used productively for flight related research.

At Universiti Sains Malaysia, the research and development of UAV is conducted by the School of Aerospace Engineering since 2002. The first prototype of the UAV namely Tamingsari was developed by Rachman (2007); this UAV was of medium type. This research initiated the development of small hand launch UAV namely AEROMECH I in 2008. Since the design of AEROMECH I is already frozen, further analysis must be done to determine whether the design is stable, trimable and controllable. Research and development of UAV AEROMECH I will produce promising results towards the development of fully autonomous capabilities for UAV, and bring the core autonomous flight control system to an advanced stage of development.

In order to make UAV AEROMECH I fully autonomous, an autopilot is needed, which controls every movement of the vehicle. It seems very simple at first, but the complexity of the equations of stability and control necessitates complete knowledge of the aircraft parameters. The aircraft has a complete collection of sensors all around that work with the autopilot, which take care of every movement of it but to correct these movements and to control the aircraft itself. It is essential to know the entire aerodynamic coefficients in order to solve the stability and control equations.

1.2 Specifications of UAV AEROMECH I

The School of Aerospace Engineering, Universiti Sains Malaysia, has designed and developed the UAV AEOMECH I for aerial surveillance and reconnaissance. The design specifications of UAV AEROMECH I are given in Table 1.1 and its various views are shown in Figure 1.2.

Table 1.1: Specifications of UAV AEROMECH I

Parameter	Value
UAV length	1.32 m
Gross take-off weight	4.5 kg
Payload	2.0 kg
Wing span	1.8 m
Wing airfoil	Eppler 423
Cruise speed	55-85 km/h
Horizontal tail span	0.39 m
Vertical tail span	0.24 m
Horizontal and vertical tail airfoil	NACA0012
Endurance	1 hour
Altitude	100 m – 300 m

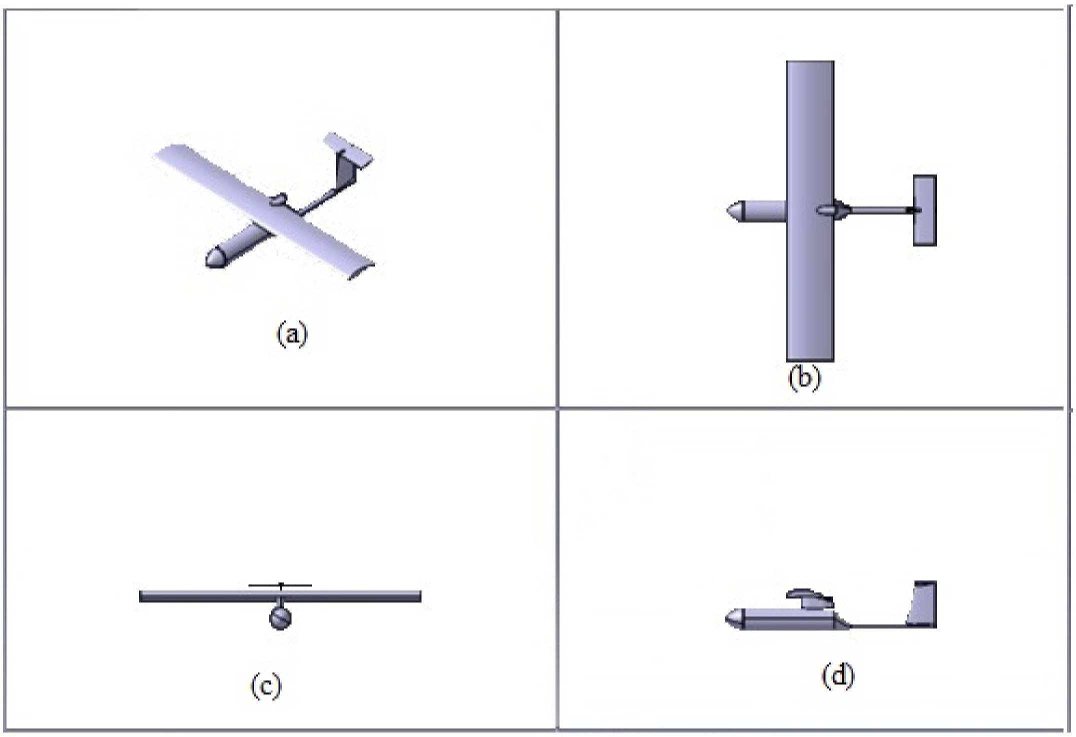

Figure 1.2: a) isometric view, b) top view, c) front view, d) side view of UAV AEROMECH I

1.3 Problem Statement

Predicting the stability of an unmanned aerial vehicle (UAV) AEOMECH I is important during the early design phase. Usually, the wind tunnel test and flight test are performed to collect the stability data (Jeffery, 2006). Unfortunately, both approaches are time consuming and expensive (Yoon et al., 2005). It generally involves model building, testing, analysing and interpreting the results. Cost will be even higher if the option to rely on the experimental approach is taken at the preliminary design phase. The experimental approach incurs a lot of other costs such as those for renting wind tunnel, renting area for flight test, expert personnel, travel, and insurance.

The "wind tunnel in the sky" approach has many hazards associated with it that can have disastrous consequences. This approach is convenient when new design is very similar to the previous tried and tested version, or engineers have enough experience and knowledge that prevent them making serious mistake. It takes almost a year to materialize the model from concept to stability data (Razgonyaez et al., 1995). Other than wind tunnel test and flight test, Computational Fluid Dynamics (CFD) are use to predict the stability of the aircraft. Even though CFD is more convenient than wind tunnel and flight tests for predicting stability in the preliminary design, CFD is still time consuming and expensive. Moreover, CFD has high computational cost and needs a supercomputer to run the analysis efficiently (Hauser et al., 2000).

It is very important to finalize and verify the design at the initial design stage itself before the fabrication of a model. Hence, in order to authenticate and optimize the model, Data Compendium (DATCOM) method will be utilized to estimate and analyze the stability of UAV. This method is easy to apply, economic, faster for generating the stability and control coefficients, and is accepted as the valid method for the aerospace applications (Anton et al., 2009; Anton et al., 2010). Usually this method is used for analyzing the stability of big aircraft (Razgonyaez and Mason, 1995; Guinta 1997; Abzug and Larrabe, 2002; Raymer and McCrea, 2000), and not yet applied on small UAV design. As known, DATCOM can generate the stability and control coefficients faster compared with the flight test, wind tunnel test and CFD. Flight test, wind tunnel test and CFD cannot generate the stability and control coefficient directly; they need to collect the aerodynamic data and then calculate the stability and control separately. For the aforementioned reasons, the DATCOM is used to estimate and analyze the stability coefficient of UAV AEROMECH I.

1.4 Project Objectives

a) To develop well documented procedure of the estimation and analysis of stability of small hand launch UAV of UAV AEROMECH I

b) To generate stability derivatives which includes $C_{L\alpha}$, $C_{m\alpha}$, $C_{Y\beta}$, $C_{l\beta}$, $C_{n\beta}$, C_{mq}, C_{lp}, C_{np}, C_{nr}, and C_{lr} via DATCOM

c) To compare the generated stability derivatives with the value from semi-empirical method (hand calculation) in order to verify the DATCOM applicability for small UAV analysis

1.5 Thesis Organization

Chapter One gives s brief review and background of UAV research in the world and development of UAV in Universiti Sains Malaysia (USM). The specifications of UAV AEROMECH I are also mentioned here, followed by the Problem statement and objectives.

Chapter Two consists of a comprehensive review of the pertinent literature in this field. The focus and concentration here are on the estimation and analysis of the stability of UAV using a different method such as Computational Fluid Dynamics (CFD), Wind Tunnel Measurement, Flight Test Measurement and DATCOM.

Chapter Three will describe the theory of stability. It will consist of concepts and definition of stability and their coefficients.

In Chapter Four, the flow chart of the DATCOM programming and the description of parameter inside the DATCOM are presented to provide more understanding for user to use the DATCOM.

In Chapter Five, the outputs from DATCOM are discussed. Here, the results from DATCOM are compared and analysed with those obtained from semi-empirical method (hand calculation) and typical stability value of aircraft.

Finally, Chapter Six presents the conclusion and suggestions for possible future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The development of Unmanned Aerial Vehicle (UAV) has long been an important issue around the world. The increasing interest in UAV has resulted in a rapidly growing number of organizations, both military and civilian, conducting research to develop fully autonomous UAVs (Tsach et al., 1996; Vitali et al., 1996; Reinhardt et al., 1999; Allouche, 2001; Tsach, 2002; Goraj, 2003; Cox et al., 2004; Patterson and Brescia, 2007). During design, the researchers have used different methods for estimation and analysis of the stability of UAV such as flight testing, wind tunnel testing, and computational fluid dynamics (CFD). These methods are time consuming and very expensive. Thus, the researchers are driven to employ a more convenient and faster method of obtaining the desired stability coefficients. DATCOM has been emerged as the right tool to meet such requirement.

In this chapter, the background information about the research on UAV and aircraft that has been carried out by other researchers is described. Besides this, methods utilized for the analysis of UAV and aircraft characteristics are also discussed.

2.2 Flight Test

The estimation of aerodynamic, stability and control, and performance derivatives of aircraft from flight test measurement is an established and well developed experimental process. The derivatives are obtained indirectly from the sensor that measure force and moment acting on the airframe. Researchers used the flight test to verify the design of aircraft because some derivatives could be easily estimated with a high degree of confidence. Other than that, the flight test is used to reduce the technical risks in a new system or subsystem, to answer design questions to some degree, and to provide necessary confidence before moving to the next phase of design with better technical, schedule, and cost information and estimates for the system (Department of Defence, USA, 1993).

You and Shim (2010) used the flight test to verify the proposed formation guidance law of KAIST Firefly UAV. The KAIST Firefly is a tailless aircraft with a reflexed thin airfoil. It is equipped with a rudder and an elevator with a vertical tail. The autopilot system of KAIST Firefly consisted of a flight control computer, an inertial measurement unit (IMU), a Global Positioning System (GPS) receiver and a pulse width modulation (PWM) generation board. The flight computer used was a PXA270 400 MHz processor with 64 MB RAM and 16 MB flash memory with weight only 25 g. The Computer Processing Unit (CPU) had the capability to moderate navigation and control algorithms without any difficulties. The autopilot software used C++ language as source code that was embedded on Linux 2.6 kernel. It was built in a structured and modular manner so that it could easily be modified to integrate new capabilities such as the formation control. The flight test was done in the condition of leader vehicles states provided for formation guidance such as position, velocity, acceleration and attitude. Since the broadcast of such information over communication was used, the Ground Control Station (GCS) was needed for receiving and broadcasting all vehicle states in real time. For this situation, each vehicle transmitted the flight states to GCS at a constant sampling rate. Proper sampling rate was chosen for the flight data broadcast so that the formation control did not suffer from data lag or drop. In the flight test, after the leader was launched and engaged in the autonomous mode, the follower was launched. The ground pilot initially flew the follower near to the leader manually. Then, the follower was commanded to enter the formation flight mode. As a cooperative formation scenario, the leader vehicle flight states were transmitted to the GCS. Then, the GCS broadcasted all neighbouring vehicles' states back to all participating vehicles in the formation. The results from flight test showed that the follower could maintain the formation with the leader within the acceptable error bounds.

Suk et al., (2003) discussed the system identification and stability evaluation of UAV from automated flight test. A variety of flight tests were performed for the system identification of UAV. A flight motion in the longitudinal open-loop flight test was excited by the elevator while the throttle was fixed to the trim throttle. In order to decouple the longitudinal mode from the lateral/directional mode, the lateral/directional autopilot was engaged to keep the wing level. The flight data were stored in Aircraft Data Acquisition System (ADAS) with a sample rate of 50 Hz. Longitudinal flight tests were performed at the altitude of around 1000 m and 500 m at various airspeeds. On the other hand, additional flight data were gained from the closed-loop pitch test. The pitch control loop consisted of two individual feedback paths such as the pitch rate and the pitch tracking error between the pitch command and pitch response. The flight test data were carefully obtained by considering consistency and reproducibility. The results from flight data were effectively used for the system identification of the UAV. As a result of the system identification, dynamic characteristic of the developed UAV were analyzed and the performance of the UAV was investigated. The results from flight test were proved that the UAV had good stability characteristics.

Motter and Logan (2006) used simulation and flight test on a UAV controls test bed. The objective of the research was to develop a small test platform controlled by a commercially available autopilot that had capability for stabilizing, navigating and recording the flight data for a small aerial vehicle in the 2-5 kg range. The UAV that used for flight test was basically a modified Army target drone, AN/FQM-117B that was developed by Aviation Applied Technology Directorate (AATD) and NASA Langley Research Centre. The UAV was equipped with on board autopilot and had Ground Control Station (GCS). The conditions for the flight test plan were: auto take-off (climb to 400 feet with speed 55 kts); pitch test 1 with aerodynamic control deflection angle range from 0-5 degrees for climb to 800 feet; pitch test 2 with aerodynamic control deflection angle 0, 5, 10, 15, 0 , -5, -10, and -15 degrees; independent aileron segment demos initiated from GCS; altitude and airspeed of UAV changed from GSC; the UAV descend to 400 feet with simulated approach and go around at 200 feet; set up approach to auto landing; and auto landing. The parameter identification based on the flight test data was used to refine the simulation and the following controller implementations.

Owens et al., (2009) developed a low cost sub scale aircraft for flight research. The purpose of the development was for research and demonstration of dynamic modelling and control design concepts. The aircraft used was Hanger 9 ARF Ultra-Stick™ 120 kit-built tail-dragger that was inexpensive. It only cost $200 for airframe. Therefore, the loss of the airframe would not involve high investment and schedule burdens. The flight test was followed by the guide line and approval from the NASA Langley Research Centre’s Airworthiness and Safety Review Board (ASRB) and a certificate of authority (COA) from the Federal Aviation Administration (FAA). Several preparations were made before the flight test, such as assembling the aircraft model and checking the functionality of the control surfaces and instruments. The UAV system was equipped with the flight control computer, vehicle instrumentation, and telemetry equipment. The flight computer consisted of physical interfaces for serial communication, pulse width modulation, frequency measurement, and analog input and output (I/O). Radio frequency telemetry system had direct ground control station, as well as ground data links and video transmission. Vehicle instrumentation was equipped with a Global Positioning System (GPS) based on inertial navigation system, as well as analog measures of control surface position and wing mounted $\alpha/\beta/$velocity probes. During the flight test, the consistency of the aircraft response data were measured using the technique known as compatibility analysis or data consistency check. The UAV had a sensor to measure acceleration, rate, and position associated with the translational motion of the aircraft and the rotational motion about the centre of gravity as well as the magnitude and orientation of air relative velocity. Data compatibility analysis showed that the flight data were accurate and consistent after corrections were made for estimated systematic instrumentation errors.

How et al., (2004) discussed evaluating the autonomous coordination and control algorithms using a fleet of eight UAVs. The Tower Trainer ARF 60 aircrafts were selected to perform the flight test. The aircrafts had relatively large payload capacities and easy handling characteristics. Besides that, the aircrafts were well suited for autopilot control because of their stable design for pilot training purpose. The stable characteristic caused the aircrafts to be less susceptible to upsets caused by turbulence, and the aircraft trim states were easily determined. There were some modifications made to the aircrafts to suit the mission requirement, which means that they could be quickly constructed and standardized across the entire fleet. The maintenance and repairs of aircraft were made much simpler by utilizing cheap, standardized aircraft for the fleet, and the logistics of flight tests were made much simpler by having vehicles with similar handling characteristics. In order to have a successful flight test of multi-vehicle flight, all the vehicles require satisfy minimum flight durations to ensure that there is sufficient time to handle the required ground operations. Flight times greater than 40 minutes were needed to make sure there was sufficient time to perform experiments for a fleet of four vehicles. The results of flight test were collected in two ways. The first method used receding horizon control (RHC) to generate waypoint plans in real time of a mission flown on the UAV test bed. The results from the first method showed that the low level vehicle controller was saturating at the maximum bank angle, causing roughly 40m overshoot offsets to be flown in some instances. Although the low level autopilot controllers were subsequently tuned to obtain better performance, the flight test highlighted the need for feedback on the planning level to account for the wind estimation error present. The second method used two vehicle formation flights with autonomous rendezvous using timing control. The results were collected for 22 minutes autonomous flight involving two UAVs simultaneously flying the same flight plan. Using timing control, the two UAVs were linked to the same receding horizon trajectory planner and independent timing control was performed about the designed plans. The relative position error of the two UAV was analyzed. The relative position error had shown that the vehicles were maintaining coordinated flight despite the moderate disturbance levels acting on the system.

The disadvantages of the flight test are: it needs substantial computational time, and recorded flight data of the highest quality. Besides that, flight test costs a lot of money and time. Sometimes the tests are justified and sometimes not, depending on the degree of technical advance sought in the system and the subsystems, the nature of the technical risks and the costs of risk reduction at various stages of design (Department of Defence, USA, 1993). On the other hand, flight test generally really hard to generate data for small airplanes such as UAV or Remote Control (RC) airplane because of the limitation of payload capacities (Yoon et al., 2005).

2.3 Wind Tunnel Test

The wind tunnel was used by the late 1940s because aircrafts were increasingly expensive to develop and the costs of designing unsuccessful aircraft were also growing. Aircraft designers put the efforts to model mathematically and to simulate as much of an aircraft’s performance as they could without having to build the airplane itself. The development of wind tunnel enables aircraft designer to perform aerodynamic tests and plan to improve aircraft performance. The early implementation of wind tunnel to simulate aircraft’s performance was done by Sir George Cayley (1773-1857). He used a whirling arm in wind tunnel to measure the drag and lift of various airfoils (www.grc.nasa.gov).

The wind tunnel is capable for various applications such as determination of drag, lift and moment characteristics on the airfoils, flow visualizations, heat transfer properties, and wind effect on aircraft. The capability of wind tunnel test to get the clear picture of aircraft performance makes the researchers use it as a tool to verify their design. Ruangwiset (2008) used a wind tunnel test to develop the fault detection for the configuration damage especially the damage or loss of the control surface of the UAV. The kind of fault can easily put UAV in the unstable and unrecoverable flight condition. When any configuration damage occurs, the aerodynamic characteristics of UAV will change. Thus, in order to detect the aircraft configuration damages, he proposed the more direct method by using the aerodynamic model. Furthermore, the principal component analysis was introduced in order to improve the accuracy of the estimated aerodynamic model. The wind tunnel test was performed with dynamical technique to validate the feasibility of the fault detection using the aerodynamic model. The experimental result showed that the configuration damage could be detected instantly by observing the residual of the aerodynamic force coefficient. Thus, the method has remarkable capability to apply to UAV for the purpose of increasing the reliability and safety.

Jindeog et al., (2003) conducted a low speed wind tunnel test for full-scale of an unmanned aerial vehicle in Korea Aerospace Research Institute (KARI) Low Speed Wind Tunnel (LSWT). The objective of this experiment was to illustrate the general aerodynamic and performance characteristics of the UAV that was developed and fabricated in KARI. The wind tunnel test was performed at various model configurations with a repeatability test to confirm the reliability of measurement. The selected configurations to explore the model component build-up effects are the following: wing + body (WB), WB + tails (WBVH), WBVH + landing gear (WBVHLG), and WBVH + test boom (WBVHTB). To study the aerodynamic characteristics of UAV with model components build-up and control surface deflections, lift curve slope, pitching moment variation with lift coefficients and drag polar were examined through the results of the wind tunnel test. To measure the aerodynamic and performance characteristics of UAV, the deflection angles of control surface such as elevator, flap, aileron and rudder were changed, and angle of attacks and yaws were varied to simulate flight condition. Also drag build-up by adding model components such as horizontal and vertical tails, landing gear and test boom was gauged. With the repeatability test on wind tunnel, the acquired data guarantees a full level of confidence, and the tunnel operating conditions such as dynamic pressure and model installation are reliable.

Buschmann et al., (2004) performed a research of miniature UAV for meteorological purpose. They conducted wind tunnel tests at the Institute of Fluid Mechanics (ISM) of the Technsiche Universität Braunschweig, for determining the UAV Carolo P50 aerodynamic properties. The test was done on various conditions such as varying angle of attack from -10^0 to $+10^0$, varying sideslip angle from -32^0 to $+32^0$, varying deflection of elevator from -15^0 to $+15^0$, varying deflection of aileron from -15^0 to $+15^0$, and varying deflection of flaps from -8^0 to $+12^0$. The sideslip variation was higher comparing to the others due to the condition of the UAV that operated at flight speeds which could have the same magnitude as gusts. From the test, the lift versus drag graph was generated which could define dimensionless coefficients for the ideal lift to drag ratio and minimum glide angle. The result from wind tunnel test was validated by non-linear flight dynamic simulation tool and flight test. Very good agreement with data test was noted in all the cases.

Cristriani (2007) stated the importance of wind tunnel test in order to confirm theoretical previsions for Falco UAV Reynolds airfoil design. The wind tunnel test has been performed for the two dimensional wing sections and for a complete UAV configuration. The scale of wing that was used for testing was 650 mm for chord and 600mm for span. The aluminium-model was instrumented with an internal balance for a quick reading of forces and pitching moment. The model also had over 100 pressure taps to provide the detailed pressure distribution over the main and flap elements of the wing section. A wake rake for drag measurements was installed about 1 chord length downstream the wing section. The wind tunnel test was used for confirming the results of CFD analysis. Observation showed that there was some slight adverse effect which was 10% loss of lift in the performance of the wing section due to maximum lift coefficient decreasing with free air stream speed. Another difference that was observed from the wind tunnel test was some uncertainty in bubble behaviour, whose presence was rarely observed on the main element even at the lowest Reynolds numbers. Explanation about this phenomenon was unclear, because the distribution of pressure tapping on the airfoil was too coarse to adequately capture the bubble shape. They argued that the higher turbulence level probably caused some changes in the transition mechanism, which was not favourable to improve the wing section performance, especially in terms of overall drag.

Cummings et al., (2007) performed numerical predictions and wind tunnel experiment for a pitching unmanned combat air vehicle (UCAV), Boeing 1301 UCAV. A 1:46.2 scale of UCAV was tested in the USAF Academy 3 ft × 3 ft (0.914 m × 0.914 m) open return low-speed wind tunnel. The UCAV had mean aerodynamic chord of 0.133 m and reference wing area of 302.1 cm^2. The test was conducted with free stream velocity of 20 m/s, according to a chord-based Reynolds number of 1.42×10^5 and the model was sting-mounted from the rear. Force and moments were measured during the test with a six-component force balance with a normal force range of 223N. Both static and dynamic testing was done. The dynamic data were obtained by subtracting the force history with the tunnel off from dynamic data. The test measurement was calibrated with the $\pm$ 0.5 % accuracy of the full measurement force of balance or 1.12 N. The precautions were made during the measured maximum force which only 15% and 20% of the full range of 223N which could further add error to the experimental data. The lift and drag coefficients were only accurate to ± 1.9% partially due to inaccurate readings of the room static pressures on the testing days. The model was suspended from downstream using a C-shaped bracket with a centre mount for the balance and model. The bracket was mounted vertically in the test section to make a vertical axis through the centre of the tunnel as a centre of rotation. The experimental results of wind tunnel test were compared with the computational results for both static and pitching cases. There were some errors between the computational test and wind tunnel test, on the pitching cycle characteristics. On the wind tunnel, the experimental 1301 UCAV results actually gained lift during the pitch-up cycle and lost lift during the pitch-down cycle. The computational results showed a lift enhancement during the entire cycle, with the difference probably being caused by the aeroelastic effects on the wind tunnel model.

Jung (2004) used wind tunnel test and flight test to verify micro air vehicle (MAV) aerodynamic characteristics. The test was done at the University of Florida, Department of Mechanical and Aerospace Engineering. The advanced equipment consisted of a six component, high sensitivity sting balance that digitally measured lift, drag, and side-force loads, as well as the three moments about the balance centre. The sting balance was connected to an automated PC data acquisition system. The MAV was held by a drive from an arm which was connected with brushless servomotor. The servomotor was operated by a single axis motion controller. A modified horizontal tail was fabricated with 5 layers of bidirectional carbon fibre and was used to aid in suspending MAV from the sting balance. The pitch or yaw angle could automatically be set to any time-variable angle of attack.

Even though wind tunnel test has proven the ability to determine aircraft characteristics with high accuracy, it still has a disadvantage. Most wind tunnels cannot accommodate real life scaled down model in the experiment. It is due to the cost of handling full sized model and the limitation of the test section size.

2.4 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) software solves the complex equations of fluid motion. CFD enables the calculation and visualization of the aerodynamic flow fields of objects moving through fluids such as air or water. The CFD capability attracted people's attention since 1970s when it was used in aerospace applications for simulating transonic flows. Embedded shock waves were automatically captured and the design process of commercial aircraft drastically changed since then (Lynch, 1982). In the early 1980s, the equations to be solved have changed from non-linear potential to Navier-Stokes equations for research application (Rumsey et al., 1997).

The potential of CFD makes it a useful tool for researchers for the analysis of the aircraft characteristics both for conventional and unconventional configurations, in the early design stage. Casas et al, (2008) used CFD in the preliminary design to study the horizontal and vertical stabilizer characteristics of medium size UAV, Spartan Phoenix. Both surfaces used a NACA 0012 as an airfoil. The CFD analysis of the surfaces was run at various free streams and various angles of attack. The free streams and angles of attack conditions selected for running the simulation were, 45m/s airspeed at 0^0 angle of attack and 20 m/s airspeed at 8^0angle of attack, with pressure and temperature at 1atm and 300K, respectively. The simulation results were compared with the results from Sub2D and the Institute of Computational Fluid Dynamics (iCFD), and found in good match.

Markham (2008) used the CFD as tool for development and optimization of the ADFA SAE Aeronautical Design UAV. The 2D CFD analysis was run on canard and wing root airfoil to determine the lifting characteristics for both the lifting surfaces. The validation of the result from CFD included comparison of the lift curve of the UAV airfoil's with existing data, and comparison of CFD velocity contour plots between both lifting surfaces with the behaviour observed in the flow visualization experiment. Following agreement between experimental and published data with CFD results, the CFD model was deemed validated.

Wisnoe et al. (2009) used the CFD for analyzing the blended wing body (BWB) of UAV at Mach 0.1 and Mach 0.3. The aim of the analysis was to measure the basic aerodynamics coefficients that contribute to the stability of aircraft such as lift coefficient, drag coefficient and pitching moment coefficient. The CFD results were compared with the wind tunnel test of 1/6 scaled half model of the BWB at Mach 0.1 and Mach 0.3. The results obtained from wind tunnel test were much smaller when compared to the CFD results. Thus, the authors recommended improving the wing to delay the flow separation by changing the airfoil of the wing, increasing the wing area and twisting the wing to delay the separation to get better results.

Sweeten (2010) used CFD to study the flying qualities of three different UAVs. The UAVs under study were 1/3 scale YAK-54, the MantaHawk, and the Meridian. The CFD results were compared with the values found from the Advanced Aircraft Analysis software. It was found that the results for YAK-54 were close to each other for both software results but varied largely for the other two UAV. The result varied due to the complexity of the aircraft design. Flight test data was also used to help determine how well each program estimated the stability and control derivative or flying qualities.

Ganglin (2009) used the CFD to determine the key parameters and conceptual configuration of Unmanned Combat Aerial Vehicle (UCAV). Analysis of the nature and characteristics of UCAV was the first step in the early design stage. Then the principles of selecting take-off weight ratio and take-off weight of attack UCAV were presented by analyzing the statistical data of weight for various main combat aircraft. The different types of engines were also analyzed and only one was chosen that met the specification of the design. The analysis of these principles guided the author to obtain longer endurance of aircraft with small aspect ratio configuration, high lift drag ratio, and internal space. This analysis also guided in proposing blended flying wing and lifting body concept. The optimization of UAV was done using CFD and verified by wind tunnel test organized by China Aerodynamics Research and Development Centre (CARDC). The test conducted on CFD with the iteration underwent 8 rounds and more than 50 different combinations of various parameter values. Each of the various parameter values represented a certain form of flying wing and lifting body conceptual configuration. Meanwhile, the wind tunnel test with UCAV conceptual configuration had a small aspect ratio of 2.8 and a maximum trimmed lift-drag ratio of exceeding 16 was conducted. The results showed good agreement between them with acceptable error.

Hitzel et al., (2009) has discussed the multidisciplinary optimization of a UAV, by combining CFD and Computational Structural Mechanics (CSM). The analysis was done only on the wing of UAV. The Computer Aided Design (CAD) model and the unstructured chimera mesh generated with the MAS MESHER were used to compute the aerodynamic force. The CAD model also provided the FEM mesh which was used by the structural analysis system NASTRAN to compute the stresses of the wing structure. The optimization analysis was steered by mode FRONTIER. The proposed tools were proved to be excellent to handle such a multidisciplinary design optimization problem.

Mohd Ali (2004) focused on the aerodynamic characteristics of USM EFA-1 Remotely Piloted Vehicle (RPV) using the CFD. The analysis was done in different Reynolds Numbers, i.e.,1.05×10^5, 1.26×10^5 and1.6×10^5, at different angle of attack. The CFD predictions of stall angle, lift, and drag coefficients were compared with the result from the open circuit wind tunnel test. Lift and drag results from CFD and wind tunnel test showed fairly good agreement. However, the CFD simulation could not predict the stall phenomena at stall angle due to limitation of the turbulence model.

Even though CFD methods are successful, it is still expensive and there must be approximation errors associated with them (Nugroho et al., 2009). CFD methods require the construction of a grid to fill the flow field volume of interest, resulting in a large number of mesh points. This consequently leads to a very large system of equations that demands the use of supercomputer which is very expensive. Smaller companies and research institution simply cannot afford these systems. Thus, the very high up-front cost of CFD analysis placed the technology beyond the reach of many the researchers and engineers whose applications could benefit the most from the new abilities of CFD codes (Hauser et al., 2000). Besides that, CFD may take many hours for a single design point analysis and thousands of analyses are needed during a single design optimization cycle. In addition, the results often contain small