DEVELOPMENT OF A SUBSCALE AIRCRAFT FOR FLUTTER TEST PLATFORM

TAN CHUN KHUEN

SCHOOL OF AEROSPACE ENGINEERING
UNIVERSITI SAINS MALAYSIA
2019

DEVELOPMENT OF A SUBSCALE AIRCRAFT FOR FLUTTER TEST PLATFORM

by

TAN CHUN KHUEN

Thesis submitted in fulfilment of the requirements for the bachelor's degree of Engineering (Honours) (Aerospace Engineering)

June 2019

ENDORSEMENT

I, Tan Chun Khuen hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

(Signature of Student)

Date:

(Signature of Supervisor)

Name:

Date:

(Signature of Examiner)

Name:

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:

ACKNOWLEDGEMENTS

I, Tan Chun Khuen have taken efforts in this Final Year Project (FYP). However, this will not be possible without the help and guidance from many individuals. Thus, I would like to take this opportunity to extend my gratitude to them.

First, I would like to express my greatest gratitude towards my supervisor, Dr. Norizham Bin Abdul Razak for his guidance, advice as well as support along the journey to complete this project. Besides, he had provided many important information, techniques and knowledge that is necessary for this project to me.

I would also like to express my gratitude towards Dr. Ho Hann Woei, Mr. Mohd Amir bin Wahab**,** Mr. Mohamad Zihad Mahmud and others for their kindness, technical support and time for me to complete this project successfully.

Finally, my thanks and appreciations also go to my course mate Low Jianyan and kind individuals who have helped me out with their abilities during the fabrication and instrumentation process. The skills, knowledge and experiences that I gained from this project will be a valuable and essential component in my future career development.

DEVELOPMENT OF A SUBSCALE AIRCRAFT FOR FLUTTER TEST PLATFORM

ABSTRACT

The interest in building High Altitude Long Endurance (HALE) aircraft are increasing rapidly recently due to its potential benefits on military and commercial usage. However, flutter is always an aeroelasticity issue as these aircraft usually has long, thin and high aspect ratio wing. Thus, it is helpful to develop a subscale aircraft with flutter test capability to investigate the effect of aerodynamic, inertia and elastic forces that act on the flexible wing. In this project, a low-cost, university-level platform is designed and developed. The design was being made to achieve the objectives of this project. Thus, its flight performance in terms of aerodynamics, stability and control, total weight and instrumentations were achieved by using XFLR5, Excel, Arduino and SolidWorks. Next, the aircraft was fabricated with Expanded PolyProplyene (EPP) foam and Depron Extruded Polystyrene (XPS) foam according to the design. Then, a total of 6 flight tests were done, and it took off successfully 3 times. Improvements were being made to initiate flutter. However, flutter was failed to be initiated as the stiffness of the wing is difficult to be tailored. Due to some accidents, the flight test was being put to a stop and Ground Vibration Test (GVT) was being carried out instead. From the GVT, the natural bending and pitching frequencies of the original wing and modified wing are 3.745 Hz, 84.28 Hz, 6.193 Hz and 118.1 Hz respectively. For the empennage's horizontal and vertical stabiliser, the natural bending frequencies are 8.324 Hz and 7.643 Hz respectively.

PEMGEMBANGAN PESAWAT UDARA SUBSKALA UNTUK TUJUAN PENGAJIAN ‘FLUTTER’

ABSTRAK

Minat dalam pembinaan pesawat ‘High Altitude Long Endurance’ (HALE) meningkat dengan pesat pada masa kini kerana manfaatnya yang berpotensi untuk penggunaan tentera dan komersil. Walau bagaimanapun, flutter merupakan masalah aeroelasticity yang biasa kerana pesawat jenis ini mempunyai sayap yang panjang, nipis dan bernisbah tinggi. Oleh itu, adalah berguna untuk membangunkan pesawat subskala dengan keupayaan ujian ‘flutter’ untuk menyiasat kesan daya aerodinamik, inersia dan elastik yang bertindak pada sayap fleksibel. Dalam projek ini, satu platform yang murah direka dan dibangunkan. Reka bentuk yang dibuat mesti mencapai matlamat projek ini. Oleh itu, prestasi penerbangannya dari segi aerodinamik, kestabilan dan kawalan, jumlah berat dan instrumen dicapai dengan menggunakan XFLR5, Excel, Arduino dan SolidWorks. Seterusnya, pesawat itu dibuat dengan busa Expanded PolyProplyene (EPP) dan Depron Extruded Polystyrene (XPS) mengikut reka bentuk. Kemudian, 6 ujian penerbangan dilakukan, dan ia berjaya berlepas dalam 3 penerbangan. Penambahbaikan telah dibuat supaya ‘flutter’ berlaku. Walaubagaimanapun, ‘flutter’ tidak berlaku kerana kekakuan sayap susah diubah dengan tepat. Disebabkan kemalangan berlaku, ujian penerbangan telah dihentikan dan diganti dengan Ujian Gegaran Tanah (GVT). Dari GVT, kekerapan lenturan dan ‘pitching’ sayap asal dan sayap diubahsuai adalah 3.745 Hz, 84.28 Hz, 6.193 Hz dan 118.1 Hz masing-masing. Kekerapan lenturan bagi ekor mendatar dan menegak adalah 8.324 Hz dan 7.643 Hz masing-masing.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

a_o	:	Airfoil lift slope
AR_{wing}	:	Aspect ratio of wing
b_{wing}	:	Wingspan [m]
C_d	:	Induced drag coefficient
C_{D_wing}	:	Drag coefficient of wing
C_l	:	Lift coefficient of airfoil
C_{L_wing}	:	Lift coefficient of the wing
$C_{m\alpha}$	:	Moment slope coefficient
C_{m_o}	:	Moment coefficient at zero angle of attack
c_{wing}	:	Mean aerodynamic chord of wing [m]
D_{wing}	:	Drag of wing [N]
L_{wing}	:	Lift of wing [N]
S_{wing}	:	Area of the wing [m^2]
V	:	Airspeed [m/s^2]
α	:	Angle of attack [°]
ρ	:	Density of air at sea-level [1.225 kg/m^3]
μ	:	Dynamics viscosity of air at sea-level [1.789 x 10^{-5} kg/m/s]

CHAPTER 1

INTRODUCTION

This chapter discusses the general overview of High-Altitude Long Endurance (HALE) aircraft and the flutter test in aeroelasticity. Besides, the problem statement and the objectives of the project that need to be achieved are being stated in this chapter. Lastly, a thesis layout that describes the content of each chapter briefly is included to give an overall picture for this thesis.

1.1 General Overview

High altitude long endurance (HALE) aircraft is a type of aircraft that can fly in the stratosphere. As an example, Boeing Phantom Eye is a HALE UAV that can make the stratosphere accessible and affordable by its ability to fly at 65,000 feet up to 10 days without refuelling (Boeing, 2018). Its endurance can be elongated to 20 days endurance at a lower altitude of 20,000-25,000 ft. Thus, HALE aircraft able to provide affordable, ultra-persistent intelligence, surveillance and reconnaissance, missile defence or other missions. A picture of the Boeing Phantom Eye is shown in Figure 1.1. Besides, HALE aircraft even has the potential to compete with satellite to carry out missions especially in communication and surveillance due to high cost and difficulty of maintaining the satellites (Kaya, 2015).

One of the main characteristics of HALE aircraft is its long and thin flexible wing which is very different from commercial aircraft which has a relatively short wing. Thus, the wing will experience large deformation during cruise flight and this is a challenge for the wing structure (S. Cesnik et al., 2012).

Figure 1.1: Boeing Phantom Eye (Boeing, 2018)

As the wing of the aircraft becomes more and more lightweight and flexible, especially for HALE aircraft, flutter has become the major threat to the structure of the wing. Hence, it is crucial to explain aeroelasticity first as flutter is one of the aeroelasticity phenomena. Aeroelasticity is defined as the reciprocal interaction of aerodynamic and inertial forces in flexible elastic structures (Razak, 2017). A Collar's aeroelastic triangle is shown in Figure 1.2.

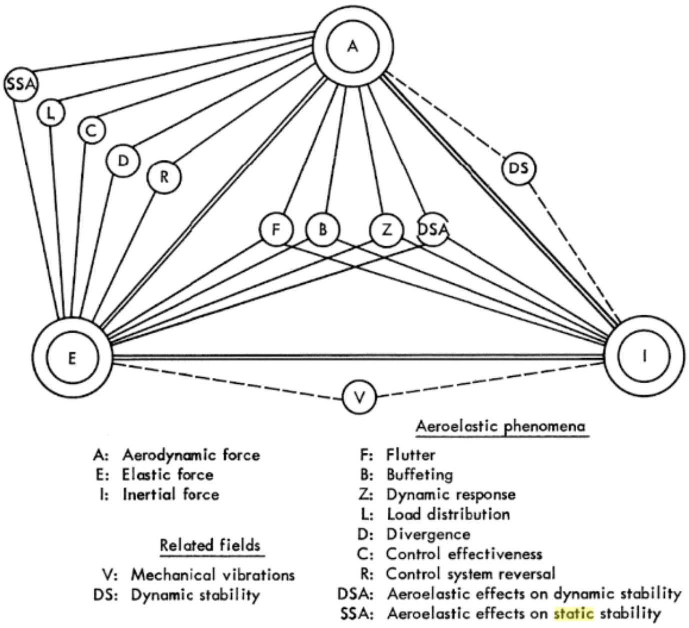


Figure 1.2 Collar's Aeroelastic Triangle (Bisplinghoff, 2013)

In general, there are two types of aeroelastic phenomena which are static and dynamic. Static aeroelasticity includes all the phenomena that do not involve oscillation, and that are independent of the mass properties of the aircraft structure (Bisplinghoff, 2013). In other words, static aeroelasticity involves the interaction between elastic and aerodynamic forces. One of the examples of static aeroelastic phenomena is the decrease of control surface efficiency at high airspeeds (Heinze, 2005). In order to increase lift especially during take-off, the aileron is deflected downward. However, a nose-down moment is produced at the same time due to the lift produced in trailing edge. This moment twists the entire wing, causing a negative lift which decreases the control surface efficiency.

Dynamic aeroelasticity involves all the three forces which are aerodynamic, elastic and inertial force (Razak, 2017). The dynamic aeroelastic phenomena include flutter, buffeting and dynamic response on the wing structure. One of the most crucial and influential problems is flutter. The unstable vibration, known as flutter, of airfoil sections is also due to the lift developed by the air flowing around the airfoil. The classical flutter usually involves the coupling of two or more degrees of freedom (Bisplinghoff, 2013, Dewey H. Hodges, 2002). Meanwhile, the nonclassical flutter is difficult to analyse on a purely theoretical basis. It may involve separated flow, stalling conditions and time-lag effects between the aerodynamic forces and the motion.

The aspect ratio and planform of the wing have a significant effect on flutter characteristics (Bisplinghoff, 2013). The decrease in wing aspect ratio and increase in sweep tends to increase the flutter speed whereas increases in wing aspect ratio and decreases in sweep reduce flutter speed. Thus, flutter is the critical issue that mainly to happen frequently on HALE aircraft due to its high aspect ratio wing.

To suppress flutter, the most usual and conventional way is increasing the stiffness of the structure. However, this will lead to an increase in weight which is considered unfavourable for fuel consumption. Another way is by Active Flutter Suppression (AFS), which utilizing the control surface and various sensor to predict and respond immediately to flutter. It is an important contributor to the effective solution of aeroelastic instability problems (Livne, 2017).

1.2 Problem Statement

Recently, High Altitude Long Endurance (HALE) aircraft has been the main focus for many kinds of research due to its potential benefits on military and commercial usage (Park et al., 2018). HALE aircraft can potentially provide a significantly cheaper means of communication especially in areas where network infrastructure is lacking or non-existent compared to a satellite (Devices, 2016, Kaya, 2015, Shearer, 2011). Meanwhile, there are some examples of HALE aircraft are being developed such as Boeing Phantom eye (Boeing, 2018), Global Hawk (NASA, 2015), Global Observer (AeroVironment, 2011), and Helios (NASA, 2014b). However, flutter is always the issue as these aircraft usually has long, thin and high aspect ratio wing. Therefore, it is necessary to develop a subscale aircraft that can act as a flight flutter test platform (Hamada, 2018, Ouellette, 2013). It is helpful to investigate the effect of aerodynamic, inertia and elastic forces that act on the flexible wing. The current flutter test platform for HALE aircraft are X-HALE (S. Cesnik et al., 2012, Shearer, 2011) and the Lockheed Martin X-56 (Burnett, 2016, Grauer and Boucher, 2017). However, the current models are complicated and very costly (Burnett, 2016). Therefore, the aim of this project is to develop a university affordable platform with similar structural properties as HALE aircraft for further investigation of the aeroelastic behaviour of a highly flexible wing.

1.3 Objectives

The main objective of this project is to design and develop a subscale HALE like aircraft with highly flexible wing structure and high aspect ratio wing to act as a flutter test platform. The project scope involves designing, fabricating, instrumenting and flight testing of the HALE platform. The HALE like flutter test platform should achieve the following requirements.

- Maximum Payload Weight: 2kg
- Controllability: Able to roll, pitch and yaw
- Flutter Test Platform: various sensors and measuring devices

1.4 Thesis Layout

This thesis consists of 5 chapters which are the introduction, literature review, methodology, results and discussions, and conclusions and recommendations. In chapter 1, the general overview is stated, followed by the problem statement and the project objectives. Chapter 2 discusses the studies on flutter test and existing HALE like flutter test platform. Chapter 3 tells the overall plan and method for the execution of the project which includes design, fabricate, instrumentation, test flight and data analysis. Chapter 4 shows the aerodynamic analysis results, the outcome of the fabrication and the result of the flight test. Lastly, chapter 5 concludes the project and future recommendations are given to improve the current work.

CHAPTER 2

LITERATURE REVIEW

As the aim of this project is to develop a HALE like platform for flutter flight test, various designs and configurations of remote-controlled aircraft need to be reviewed and considered. There are many studies about flutter in modern aircraft. Hence, the review is done in term of design, instrumentation and data analysis. A few examples of HALE aircraft are the X-HALE, Lockheed Martin X56 and Boeing Phantom Eye as shown in Figure 2.1a to 2.1c. The survey can help a lot in obtaining general design concept of the HALE aircraft to fulfil the objectives that will be mentioned in the later section.

a. X-HALE (Shearer, 2011)

b. Lockheed Martin X56 (Ryan and Bosworth, 2014)

c. Boeing Phantom Eye (Boeing, 2018)

Figure 2.1: Existing HALE aircrafts for flutter test

Every existing HALE aircraft design has different missions, so their performance and characteristics are different. Majority of the HALE aircraft share a common characteristic of long, thin and highly flexible wing. The wingspan of X-HALE measures 8m and an aspect ratio of 40. Phantom Eye wingspan is even longer and stands at 45m (Boeing, 2018). This high aspect ratio wing is more efficient as it produces less induced drag for the amount of lift it generates (Anderson, 2011). In term of design, HALE aircrafts utilised classic multiple tail-boom configurations like X-HALE and Helios, while others like X56 employs Blended Wing Body (BWB) design (Grauer and Boucher, 2017, Jones and Cesnik, 2015). This unique design can have 15 to 20% of increases in lift-to-drag ratio due to its smaller wetted surface compared to conventional design (Okonkwo, 2016). However, the limitations are lack of control surfaces and control authority which leads to difficulty in flight control (Okonkwo, 2016).

In term of the propulsion system, smaller size aircraft like X-HALE utilises five PJS 1200 outrunner electric motors which produce a maximum static thrust of approximately 10N each (S. Cesnik et al., 2012). Its bigger siblings like X56 and Phantom Eye are equipped with two JetCat P400 turbo-jet engines and two 2.3 litre hydrogen-fuelled engines respectively due to their larger Maximum Take-Off Weight (MTOW) (Burnett, 2016, Boeing, 2018). This liquid-hydrogen fuel system is one of the keys systems that allows the Phantom Eye to fly at 65,000 feet for 4 days (Boeing, 2018).

The aircraft has a lightweight design for longer endurance. The material selection plays a crucial role as it must have a high strength-to-weight ratio. The common materials that can cope with it are composite materials such as carbon fibre reinforced plastic (CFRM). The X56 utilised carbon fibre for skin, spar and ribs while the foam is used the structural core (Burnett, 2016).

A flight flutter test is experimental testing of the occurrence of flutter phenomena within a new aircraft's flight envelope in real flight situation. One of the main reasons to carry out the flight flutter test is to prove the flight envelope of a new aircraft is free from aeroelastic flutter (Razak, 2017). Many authorities around the world, especially in the US like the Federal Aviation Administration (FAA), requires all aircraft manufactures to demonstrates that the flight envelope of a newly built aircraft is free from flutter (Jan R. Wright, 2015). Another common reason to execute flight flutter test is to validate the result of theoretical modelling or numerical stimulation of aeroelastic phenomena. Although the theoretical analysis offers significant advantages to examining the interactions between the flight dynamics and the structural dynamics, it is necessary to validate the theory by carrying out the flight flutter test (Ouellette, 2013).

To perform flutter test, the aircraft must be instrumented with various measuring devices and sensors. The common instrumentations are accelerometers, strain gauges and inertia measurements unit (IMU) (Razak, 2017). Besides, basic equipment to monitor the flight conditions such as pitot tube (for airspeed measurement), angle of attack sensor and GPS location are needed as well. For example, the sensors on board the X-HALE are categorized into two groups which are science and housekeeping (S. Cesnik et al., 2012). Science data include all strain gages and accelerometers used in sole support to the aeroelastic tests. The latter include sensors that monitor the health of the aircraft, such as temperature and battery voltage; flight conditions (e.g., airspeed, angle of attack, side-slip angle, Euler angles, GPS location); and control inputs (e.g., motor RPM, control surface deflections). Besides instrumentations, telemetry and ground station are an important part in the complete execution of flight flutter test. As an example, the X-56 is a complete research system which includes a Ground Control Station (GCS) used to remotely pilot the vehicle and monitor flight test instrumentation (Grauer and Boucher, 2017). The mobile ground station and different wing configurations of X-56 are shown in Figure 2.2a and 2.2b.

Figure 2.2: (a) Different wing configurations (b) Mobile ground station (Burnett, 2016)

During flight flutter test, the aircraft structural responses are measured and analysed to determine whether flutter happened or not. The usual testing parameters are airspeed, altitude, angle of attack, damping and frequency. Typical flutter test results are in terms of frequency and damping versus speed at different angle of attack and/or altitudes as shown in Figure 2.3 (Burnett, 2016).

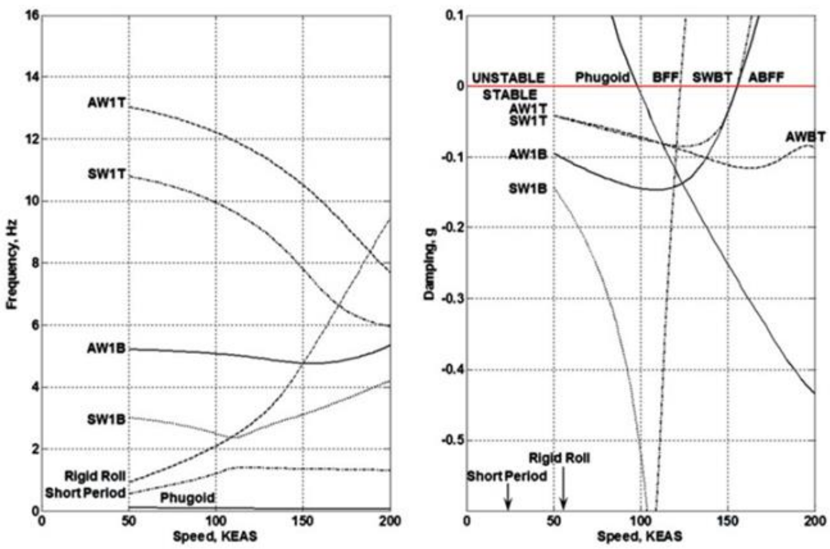


Figure 2.3: Typical velocity/frequency/damping plots of a flying-wing-type aircraft (Burnett, 2016)

Ground Vibration Test (GVT) is another common dynamic test performed on aircraft beside flight flutter test. The ground vibration test is necessary to assure the aeroelastic and aeroservoelastic stability of new and modified aircraft (NASA, 2014a). The main objective of performing a GVT on an aircraft is to collect experimental vibration data of the aircraft structure such as resonant frequencies, mode shape and damping (Peeters et al., 2008). These data are used to validate and improve structural dynamic models, analytical vibration and flight control models by comparing the experimental result and the analytical result (NASA, 2014a, BillFlynn, 2018). Depending on the type of aircraft, different fuel or store configurations will be tested with GVT to acquire different response (BillFlynn, 2018). Figure 2.4 shows the full body GVT carried out on the Lockheed Martin X56 before the flight test.

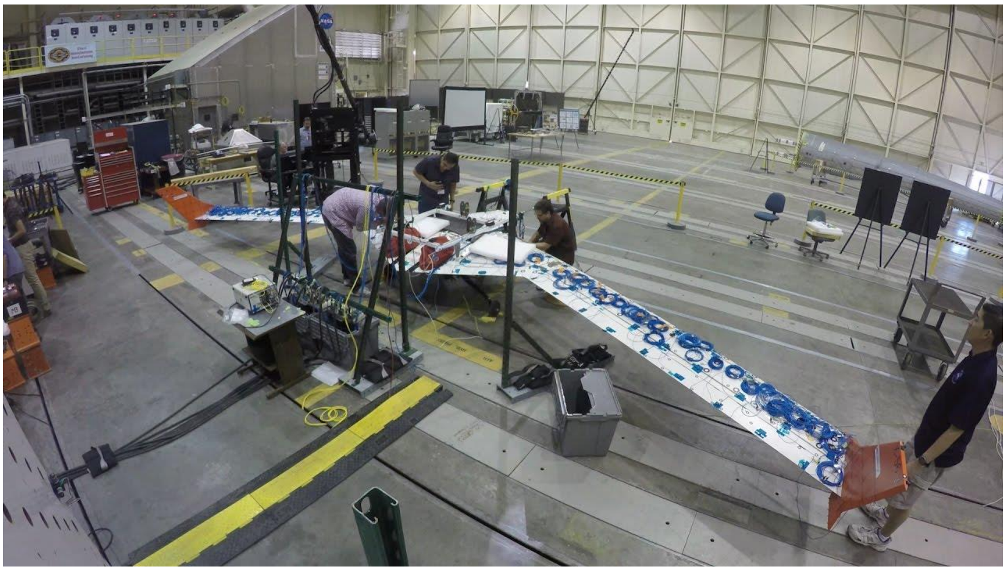


Figure 2.4: X56 full body ground vibration test (Center, 2016)

To perform the GVT, accelerometers are the main sensor used to measure the structural response of the aircraft. In typical GVT for aircraft, there are more than 300 accelerometers are being used on the whole aircraft to obtain an adequate result (Peeters et al., 2008). To initiate the vibration, shakers or exciters are being used to supply adequate citation energy throughout the entire structure to get a good signal-to-noise response (BillFlynn, 2018). Some examples of exciters are being shown in Figure 2.5.

Figure 2.5: Lateral exciter (on left side) and vertical exciter (on bottom) for an aircraft engine (BillFlynn, 2018)

CHAPTER 3

METHODOLOGY

This chapter discusses the methods and materials used in the development of a HALE like flutter test platform. Besides, the methodology in terms of conceptual design, design analysis, fabrication process, instrumentation, flight test and ground vibration test will be described in detail in this chapter.

3.1 Overview

The overview of the methodology for this project can be represented graphically by a flow chart shown in Figure 3.1. The project starts with a literature review of existing platforms that being carried out and discussed in Chapter 2. From the literature review, the requirements and objectives for the design of a flutter test platform are being obtained. The design of the HALE-like flutter test platform starts with a conceptual design first, then followed by a detailed design which utilises CAD software such as SolidWorks.

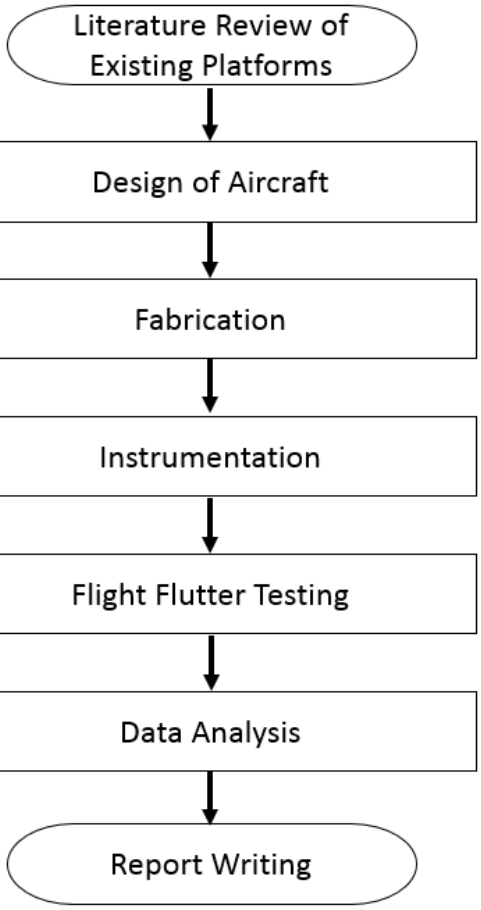


Figure 3.1: The overall methodology flow chart for the project

Next, the instrumentation is being carried out. The wiring and programming of Arduino as a data logger, micro SD card module for data storing and 5 degrees of freedom IMU sensor for collecting data such as bending frequency, pitching frequency and the corresponding time.

Then, the flight test was carried out and improvements are being made to enhance the performance and initiate flutter during the flight. After that, the data collected will be analysed in term of graphs and thesis will be written.

3.2 Conceptual Design

In this project, the conceptual design is being started with an initial sketch on a paper with an initial idea of the prototype. The initial sketch is being shown in Figure 3.2. Next, all the technical drawings are being done by utilising computer-aided design (CAD) software which is called SolidWorks.

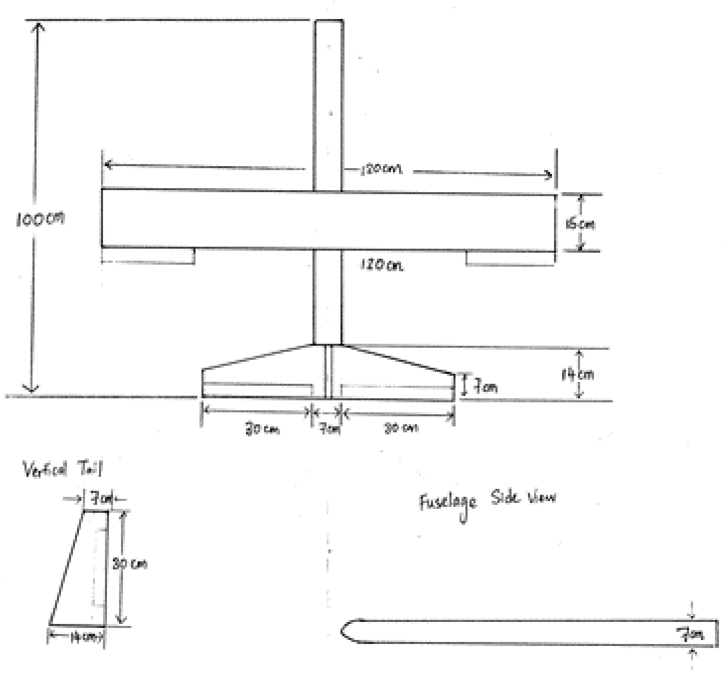


Figure 3.2: Initial sketch of AEROHALE

The HALE like flutter test platform, AEROHALE has a traditional wing-fuselage-tail configuration. It has a top wing placement for greater stability during the flight. The wing is a straight rectangular wing with a wingspan of 1.2m and a high aspect ratio of 8. The basic parameters of AEROHALE are shown in Table 3.1.

Table 3.1: The basic parameters of AEROHALE

Parameters	**Dimensions (cm)**
Wing	
Wing Span	120
Chord	15
Aspect Ratio	8
Surface Area	1800 cm^2
Fuselage	

Total Length	100
Width	8.5
Height	7.6
Empennage (Horizontal Stabilizer)	
Span	68
Root Chord	14
Tip Chord	7
Taper Ratio	0.5
Aspect Ratio	5.71
Surface Area	630 cm^2

The fuselage is designed to have a box-shape with a total length of 1m. The box-shape fuselage provides larger space for the installation of the instrumentations such as Arduino, micro SD card, battery and other electronic components. The fuselage also has a lid with a magnet inside to allow easy access to the inside of the fuselage. The leading edge of the fuselage is designed to have a rounded head for better aerodynamic performance.

The empennage of AEROHALE is a conventional tail design which consists of a horizontal and vertical stabiliser. Both stabilizers are tapered with a taper ratio of 0.5. The surface area of the horizontal stabilizer is about 35% to the surface area of the wing and the surface area of the vertical stabilizer is about half of the horizontal stabilizer (Brock, 2015). Both stabilizers are having a flat plate design for easier fabrication. The overall configuration of AROHALE is shown in Figure 3.3.

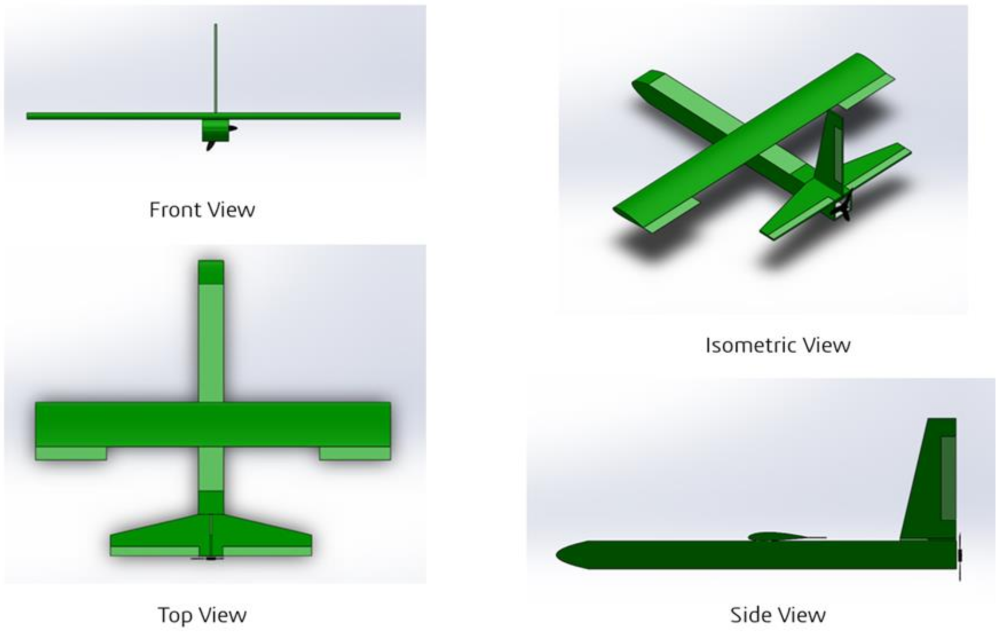


Figure 3.3: Top, front, side and the isometric view of AEROHALE by SolidWorks

3.3 Design Analysis

3.3.1 Aerodynamics

(i) Airfoil

The aerodynamics analysis of several types of airfoils is being done to evaluate their performance in terms of stall angle, lift-to-drag ratio and moment coefficient of the airfoil. XFLR 5 is used for the aerodynamic analysis of the airfoils. XFLR5 is an analysis tool for airfoils, wings and planes operating at low Reynolds numbers. It has wing design and analysis capabilities based on the Lifting Line Theory, on the Vortex Lattice Method, and on a 3D Panel Method (XFLR5, 2019).

There is a total of 6 types of cambered airfoils are being selected and analysed which are Clark W, NACA 2414, NACA 4412, NACA 6412, S2027 and S4310. The cambered airfoils are beneficial to the HALE like subscale aircraft as it usually has higher lift compared to symmetrical airfoil due to its shape to turn the flow greater, thus producing higher lift (NASA, 2018).

The lift slope of the airfoil, a_o can be formulated by using Equation (1) (Anderson, 2011).

$$a_o = \frac{dC_l}{d\alpha} \tag{1}$$

The range of the angle of attack used in the analysis is between -20° to $+20^{\circ}$ with Reynold's number of 140,000 based on the designed cruise speed of 50 km/hr. Besides, all the airfoil data such as the geometry X and Y coordinates are being taken from Airfoil Tools in the .dat file (Tools, 2019).

(ii) Wing

In the design of HALE like flutter test platform, a wing with a high aspect ratio is needed so that the wing is flexible enough to perform the flight flutter test. The aspect ratio of a wing is defined as the ratio of square wingspan (${b_{wing}}^2$) to its wing area (S_{wing}) which can be written as shown in Equation (2) (Anderson, 2011).

$$AR_{wing} = \frac{{b_{wing}}^2}{S_{wing}} \tag{2}$$

Besides, Reynolds number is an important parameter to consider during the wing analysis as it can determine whether the flow is laminar or turbulent flow. As AEROHALE is intended to fly at low speed, a laminar flow is expected. Reynolds number is defined by the density of air (ρ), the velocity of air (V), mean aerodynamic chord (c_{wing}) and the dynamic viscosity of air (μ) as shown in Equation (3) (Anderson, 2011).

$$Reynolds\ number = \frac{\rho V c_{wing}}{\mu} \tag{3}$$

After that, the lift and drag coefficient of the finite wing need to be determined in the analysis. The lift coefficient of the wing (C_{L_wing}) and the drag coefficient of the wing (C_{D_wing}) are shown in Equation (4) and (5) respectively (Anderson, 2011).

$$C_{L\_wing} = \frac{L_{wing}}{\frac{1}{2}\rho V^2 S_{wing}} \tag{4}$$

$$C_{D\_wing} = \frac{D_{wing}}{\frac{1}{2}\rho V^2 S_{wing}} \tag{5}$$

Since the aspect ratio of the wing is higher than 4, the lifting line theory is applied (Anderson, 2011). Then, by knowing the lift and drag coefficient of the finite wing from the analysis, lift and drag can be calculated by the Equation (6) and (7) respectively (Anderson, 2011). As the wing is the major lift and drag contributor for the entire aircraft, only the lift and drag of the wing is being considered.

$$L_{wing} = \frac{1}{2}\rho V^2 S_{wing} C_{L\_wing} \tag{6}$$

$$D_{wing} = \frac{1}{2}\rho V^2 S_{wing} C_{D\_wing} \tag{7}$$

3.3.2 Stability and control

(i) Stability

Flight stability is one of the essential elements in aircraft design analysis as it affects the ability of the aircraft to fly steadily and carry out some different types of manoeuvres during the flight. In this project, the static longitudinal stability of AEROHALE is being analysed by using the XFLR5 software.

As AEROHALE has a conventional wing-fuselage-tail configuration, its longitudinal stability, lateral stability, and directional stability are controlled by the elevators, ailerons, and rudder respectively. Table 3.2 shows the primary control surface and its corresponding type of stability.

Table 3.2: Principle axis and motion for an aircraft (Nelson, 1998)

No.	Primary Control Surface	Aircraft Movement	Axes of rotation	Type of stability
1	Aileron	Roll	Longitudinal	Lateral
2	Elevator / Stabilizer	Pitch	Lateral	Longitudinal
3	Rudder	Yaw	Vertical	Directional

(ii) Control Surface Sizing

Table 3.3: Typical values for the geometry of control surfaces (Sadraey, 2013)

Control surface	Elevator	Aileron	Rudder
Control surface area/lifting surface area	$S_E/S_h = 0.15–0.4$	$S_A/S = 0.03–0.12$	$S_R/S_V = 0.15–0.35$
Control surface span/lifting surface span	$b_E/b_h = 0.8–1$	$b_A/b = 0.2–0.40$	$b_R/b_V = 0.7–1$
Control surface chord/lifting surface chord	$C_E/C_h = 0.2–0.4$	$C_A/C = 0.15–0.3$	$C_R/C_V = 0.15–0.4$
Control surface maximum deflection (negative)	−25 deg (up)	25 deg (up)	−30 deg (right)
Control surface maximum deflection (positive)	+20 deg (down)	20 deg (down)	+30 deg (left)

The control surfaces of AEROHALE include ailerons, elevators and rudder. The sizing of the control surfaces is decided by referring the typical values for the geometry of control surfaces in Table 3.3.

Table 3.4: Parameters for control surfaces

Control Surfaces	Parameters	Dimensions (cm)
Elevators	Elevator Span	60.00
	Elevator Chord	3.15

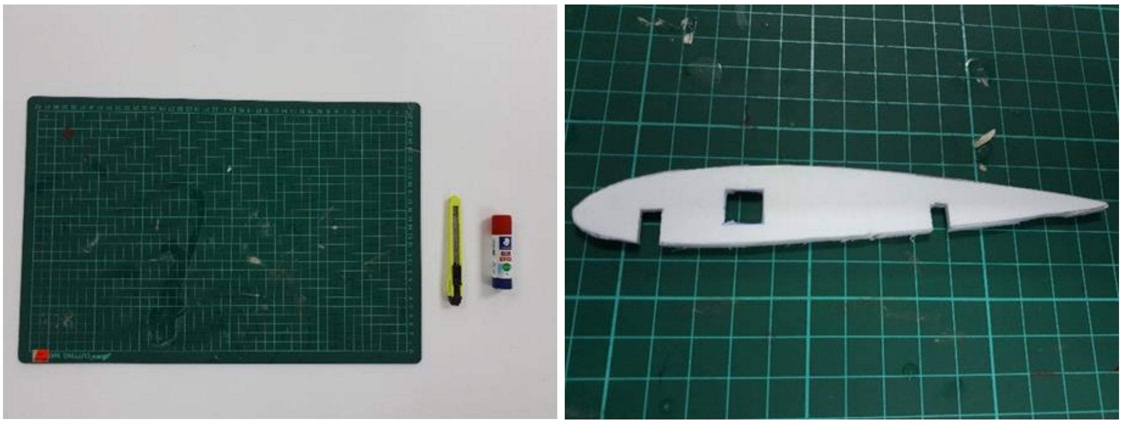
Ailerons	Aileron Span	48.00
	Aileron Chord	4.50
Rudder	Rudder Span	21.00
	Rudder Chord	3.75

Based on Table 3.4, for the elevator, the ratio of the surface area of the elevator to wing surface area is set to 0.3. The span ratio and chord ratio are set to 1.0 and 0.3 respectively. For the aileron, the surface area ratio is decided to be maximum at 0.12. The span ratio and chord ratio are set to 0.4 and 0.3 respectively. For the rudder, the surface area ratio is decided to be 0.25. Hence, the corresponding span ratio and chord ratio are set to 0.8 and 0.357 respectively. Table 3.3 shows the parameters for all the control surfaces in the corresponding surface area ratio.

3.4 Prototype Fabrication

3.4.1 Wing

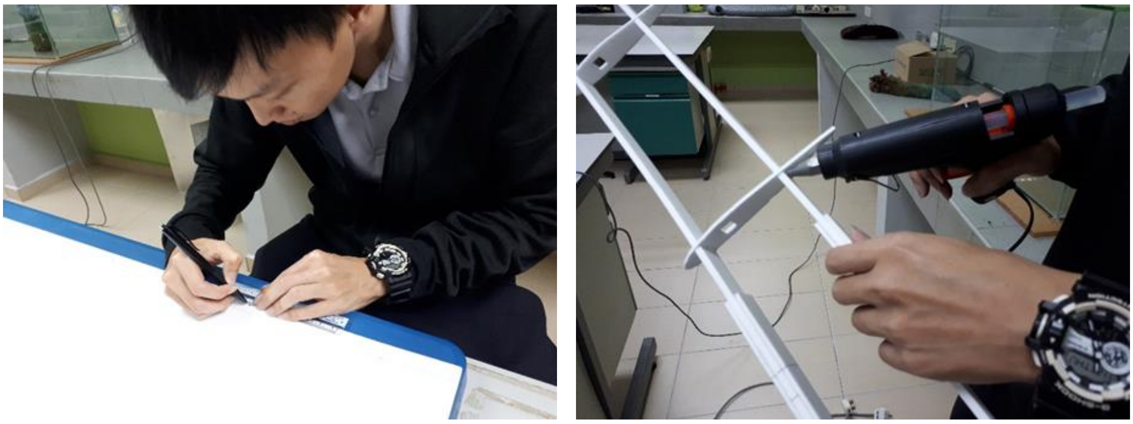
First of all, NACA 2414 airfoil was being cut out from 3mm EPP foam to use as the ribs for the wings. A square hole with 1cm long was being cut on the ribs for the wires to pass through. The front spar and rear spar were located at 16.7% and 66.7% chord to provide a larger space for the wing box. The tools for cutting the foam such as cutting board and knife are shown in Figure 3.4a.



a. Tools for cutting of foam b. NACA 2414 airfoil

Figure 3.4: Tools required and geometry of ribs

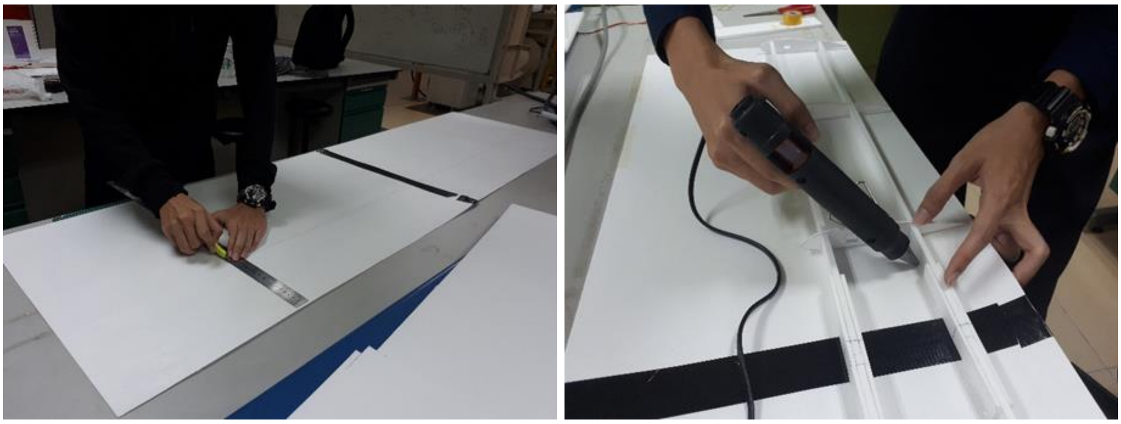
Next, the front and rear spar were drawn on the 5mm EPP foam as shown in Figure 3.5a. Both spars were cut out according to the drawing. Then, all the ribs were being glued on to the spar. Before applying glue, the contact is being made sure was clean and free from dust to ensure a strong connection. The adhesive was applied onto the contact points by using a suitable size hot glue gun as shown in Figure 3.5b.



a. The geometry of spars is drawn on foam b. The ribs are glued into the spars

Figure 3.5: Fabrication of spars

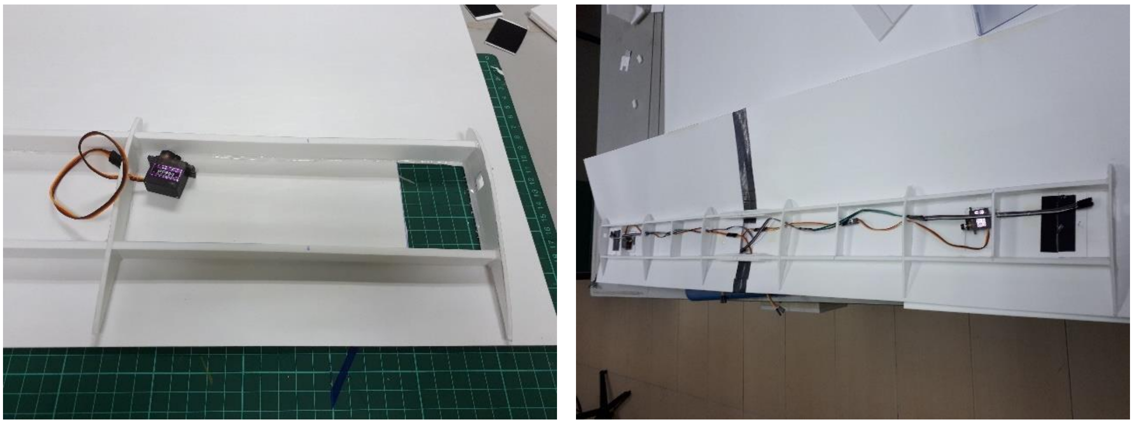
The 1mm EPP foam was cut out for the skin of the wing as shown in Figure 3.6a. The rib-spar structure was glued onto the skin precisely to ensure the skin of the wing is smooth and without any dimples.



a. Cutting of 1mm EPP foam (Skin)   b. The structure is glued onto the skin

Figure 3.6: Assembly of the wing

After that, wires are being installed into the wing for the accelerometer. A small cut out was being made at both ends of the wing for the placement of accelerometer later. Then, two servo motors were being installed on the wing to control the ailerons. The servos were glued to the ribs for extra rigidity.



a. Cut out for accelerometer placement   b. Internal view of the wing

Figure 3.7: Installation of servos and accelerometer

For the fabrication of ailerons, 2 pieces of ailerons were cut out from the EPP foam and taped on the trailing edge of the wing. Before that, control horns were installed on the ailerons. Control rods were made by a pair of metal rods, connected by a screw connector. The screw connector allowed the trimming of the control rod later. Finally, the servo and control horn were being connected by the control rod and trimming was done to make sure the ailerons were in its neutral position.

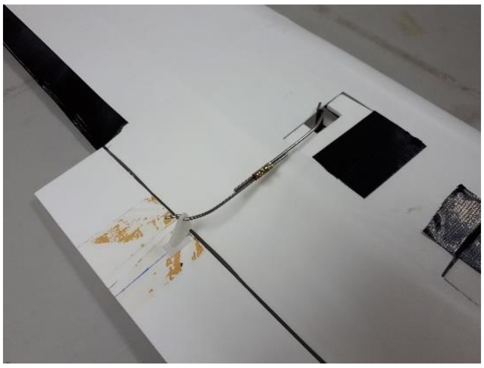
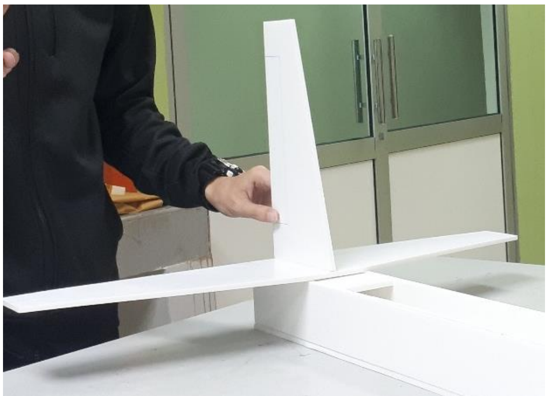


Figure 3.8: Installation of ailerons

3.4.2 Empennage

For the fabrication of empennage, the process is similar to the wing. The dimensions of horizontal and vertical stabilizers were drawn and cut out from the Depron foamboard. Both stabilizers are being glued together to form the empennage. The horizontal stabilizer was being reinforced by 2 pieces of the carbon rod. The carbon rods were being glued on the bottom of the horizontal stabilizer and covered by a black cloth tape.



a. Assembly of empennage

b. Reinforcement of horizontal plane

Figure 3.9: Fabrication of empennage

The elevator and rudder were made in a similar way with the fabrication of ailerons. A servo was installed on the horizontal tail for the control of rudder while two servos were installed on both sides of the fuselage for the control of elevators. Since there is an independent servo for each surface, so they can be controlled separately during the flight.

a. Control rod made from metal rod

b. Control rod for elevators

c. Control rod for elevators

Figure 3.10: Fabrication of elevators and rudder

3.4.3 Fuselage

In the fabrication of fuselage, the required shape was drawn and cut out from the Depron foamboard. The nose of the fuselage was built by using 5mm EPP foam for impact absorption during landing. Next, the walls and base of the fuselage were glued together. Then, an open lid with a magnet is being made for easy access to the inside of