STRESS AND AEROELASTIC ANALYSES OF ULTRALIGHT AIRCRAFT WING

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UNIVERSITI SAINS MALAYSIA

2021

STRESS AND AEROELASTIC ANALYSES OF ULTRALIGHT AIRCRAFT WING

by

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Thesis submitted in fulfillment of the requirements for the

Bachelor Degree of Aerospace Engineering (Honors)

(Aerospace Engineering)

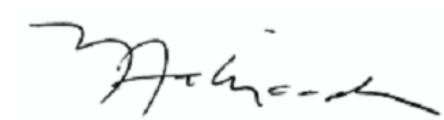
June 2021

ENDORSEMENT

I, Hussam Fatthi A Kabbarah hereby declare that I have checked and revised the whole draft of the dissertation as required by my supervisor.

(Signature of Student)

Date: **07/22/2021**



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Date: 07/22/2021

ENDORSEMENT

I, Hussam Fatthi A Kabbarah hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date: 07/22/2021

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Name: Dr Mohd Shukur Bin Zainol Abidin

Date: 22 July 2021

DECLARATION

This thesis is the result of my 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: **07/22/2021**

ACKNOWLEDGEMENTS

The success and the outcome of this final year project required a lot of guidance and assistance from many individuals, and I am very grateful for all the help that I have got during the progression of the project.

First and foremost, I would like to take this opportunity to thanks Dr. A Halim Kadarman for his unlimited patience and guidance throughout the project duration making it a success. His willingness to help and spare his time to provide me guidance and pointers is very much appreciated. I dare say, without the help of Dr. Halim, this thesis would not have come to a completion.

Furthermore, I would like to thank Dr. Aslina Anjang Ab Rahman and Dr. Mohd Shukur Bin Zainol Abidin for their patience in evaluating my thesis draft and their detailed comments to allow this thesis to improve in quality. I would like to thank them for their valuable pointers given during the colloquium session which helped me understand more about this research. I would like to also thank my fellow seniors which have researched this, Nurul Asyikin for the help she gave allowing the progression of the project to be smooth.

Lastly, I would like to thank my father and my mother for their never-ending support and motivation as well as their encouragement throughout my study life.

ULTRALIGHT AIRCRAFT WING STRUCTURE

ABSTRACT

This paper attempts to study a methodology stress analysis of an ultralight-aircraft's wing structure imperiled to certain stress loads throughout the research. The analysis will cover static and flutter analysis of the wing's structure. For static, it is more into lift distributions and the resultant stresses in a 3-dimensional axis. As a first step, the wing was modeled using SolidWorks 2020. The structural components of the wings will consist of primary and secondary spar-webs and cross-sectional ribs attached using SolidWorks 2020 Assembly. NACA 2412 is chosen as the baseline airfoil for wings. The spar-caps were used in the first model, but due to the academic edition of SolidWorks 2020, the number of elements was limited for any additional components. The wing spars and the skin covering are made of Aluminum Alloy, 7075-T6, to reduce the weight of the structure. The first section will investigate the static structural behavior of the wing to give the overall shear, bending, and torsional stresses. A V-n diagram will be established for each wing structure based on the design and flight specifications using MATLAB 2019 edition. The Corresponding Von-Mises tension and comparable elastic strain are obtained to study the mechanical behavior of the wings. Furthermore, the flutter analysis of the structure will cover the calculations of flutter speed from a modal investigation using SOLIDWORKS 2020 software. Also, the modal shape of each mode and its frequency are obtained to analyze the dynamic behavior of the wings. The outcomes from the static and dynamics structure analysis of the ultralight aircraft wings aid engineers to reduce excitation on the natural occurrences and avoid wings from flutter at higher speeds. Given the results obtained in this paper, the analysis showed safe design following FARs (Federal Aviation Regulations) which no permanent deformation and

no global buckling will occur at maximum load as well as the factor of safety of 1.5 against ultimate strength was obtained. In conclusion, the sequence of analyzing the wing's structure never ends and there is room for future improvements for accurate stress analysis and high-grade information.

STRUKTUR SAYAP PESAWAT RINGAN

ABSTRAK

Risalah ini cuba mengkaji metodologi dalam analisis tekanan struktur sayap pesawat ultra ringan yang terancam beban tekanan tertentu sepanjang penyelidikan. Analisis ini akan merangkumi analisis statik dan debar struktur sayap. Untuk statik, ia lebih kepada pengagihan angkat dan tekanan yang dihasilkan dalam paksi 3 dimensi. Sebagai langkah pertama, akan ada dua model sayap dengan dimensi dan bahan yang berbeza. Komponen struktur sayap akan terdiri daripada jarring spar primer dan sekunder serta tulang rusuk keratan rentas yang dipasang menggunakan SolidWorks 2020 Assembly. NACA 2412 dipilih sebagai landasan udara asas untuk sayap. Penutup spar digunakan pada model pertama, tetapi kerana edisi akademik SolidWorks 2020, jumlah elemen terhad untuk komponen tambahan. Penutup spar sayap dan seliput kulit terbuat dari Aluminium Alloy, 7075-T6, untuk mengurangkan berat struktur. Bahagian pertama akan menyiasat tingkah laku statik struktur sayap untuk memberikan tekanan ricih, lenturan, dan tekanan kilasan. Gambar rajah V-n akan dibuat untuk setiap struktur sayap berdasarkan reka bentuk dan spesifikasi penerbangan menggunakan edisi MATLAB 2019. Ketegangan Von-Mises yang sesuai dan regangan elastik yang setanding diperoleh untuk mengkaji tingkah laku mekanikal sayap. Selanjutnya, analisis debar struktur akan merangkumi pengiraan kelajuan debar dari penyiasatan model menggunakan perisian SOLIDWORKS 2020. Juga, bentuk mod setiap mod dan frekuensi tersendiri diperoleh untuk menganalisis tingkah laku dinamik sayap. Hasil daripada analisis struktur statik dan dinamik sayap pesawat ultra ringan membantu para jurutera mengurangkan pengujaan pada kejadian semula jadi dan mengelakkan sayap daripada debar pada kelajuan yang lebih tinggi. Dengan melihat hasil yang diperoleh dalam risalah ini, para

pereka dapat membuat keputusan yang berdasarkan hasil yang diperoleh dalam risalah ini, analisis menunjukkan reka bentuk yang selamat mengikut FARs (Peraturan Penerbangan Persekutuan) yang tidak mengalami ubah bentuk kekal dan tiada kegagalan lengkukan global akan berlaku pada beban maksimum dan juga memperolehi faktor keselamatan 1.5 berbanding kekuatan muktamad bahan. Kesimpulannya, urutan menganalisis struktur sayap tidak pernah berakhir dan sentiasa ada ruang untuk penambahbaikan pada masa hadapan untuk analisis tekanan dengan lebih tepat dan maklumat yang sangat berharga.

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LIST OF ABBREVIATIONS

CAD	Computer-Aided Design
FEA	Finite Element Analysis
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
MTOW	Maximum Take-Off Weight
MLW	Maximum Landing Weight
MZFW	Maximum Zero-Fuel Weight
MW	Minimum Weight
FOS	Factor of Safety

LIST OF SYMBOLS

ρ Density

P Pressure

T Temperature

a Speed of Sound

μ Aerodynamic Viscosity

CHAPTER 1

INTRODUCTION

1. BACKGROUND

Ultralight aircraft are known as microlight aircraft whose definitions, weight, and speed limits differ based on the FAA regulations. Ultralight aircraft is designed primarily for recreational flying for distances of not more than 165.4 kilometers (km) from a home base. Over the last three decades, several models have been developed to include Ultralight aircraft designs, which are classified by the type of structure:

1. The first-generation ultralights were actually “hang gliders” with small engines mounted at the back, for self-launching.
2. The second-generation ultralights are powered aircraft having "2-Axis" control systems.
3. The third-generation ultralights have strut-braced wings and airframe structures use “3-Axis” control systems.

Since the early 1980s, several aerospace firms beefed up their interests in building ultralight light airplanes to increase their revenues during summer airshows, see table 1. Take, for example, *Sonex Aircraft*, which is based in Oshkosh, United States of America, their annual sales were about $4.9 million, while *CGS Hawk*, which is based in Florida, United States of America, the company’s estimated annual sales reach almost $9.9 million (Cavallo, 2021). Furthermore, the CGS Hawk was debuted at Sun-n-Fun, March 1982, Lakeland, Florida where it took top honors winning "Best New Design”, see figure1 (Hawk, 2020).

Table 1: Top Ultralight Aircraft Manufacturers the USA on (Thomasnet.com)

Company	Headquarters	No. of Employees	Year Founded	Estimated annual sales
CGS Hawk Aviation	Grand Bay, AL	10-49	1981	$5-9.9 Mil
Quicksilver Aircraft	Temecula, CA	10-49	1914	$5-9.9 Mil
Sonex Aircraft	Oshkosh, WI	1-9	1998	$1-4.9 Mil
Phantom Aeronautics	Three Rivers, MI	1-9	2011	Under $1 Mil
Air-Tech Inc.	Reserve, LA	1-9	1977	Under $1 Mil
Aero Adventure	DeLand, FL	1-9	1995	Under $1 Mil
Aircraft Supermarket	De Soto, IA	1-9	1975	Under $1 Mil

Figure 1: View of the Arrow II Two-Seater Ultralight CGS Hawk

Figure 2: View of the All-metal Merlin Lite *(JOHNSON, 2020)*

Each country has different regulations and rules on ultralight aircraft. According to an informative website:

Ultralight aircraft are single/double passenger aircraft typically used for sport or recreational flying. They are controlled via weight shift control or conventional 3 axis control and can be powered using small engines or electric propulsion systems. There is considerable overlap between ultralight aircraft and light-sport aircraft (LSA), but light-sport aircraft tend to be larger, more sophisticated, have more features, and are rated for longer distances and altitudes. Depending upon the country of origin, ultralight aircraft have varying degrees of regulations on their size, number of seats, maximum takeoff weight, certifications, etc., where some ultralights in one country are valid/invalid in another, and vice-versa. A commonality across most countries is that ultralight aircraft can only be flown in uncontrolled airspace during the day (unless special permission is granted). The types of ultralight aircraft include fixed wings, powered parachutes, hot air balloons, trikes, helicopters, powered paragliders, and custom models. In the United States, ultralight aircraft are not required to be registered and pilots do not need a certificate, though flight training is strongly advised (Cavallo, 2021).

Ultralight aircraft are similar to fixed-wing large airplanes when it comes to the design phase. The design phase acquires preliminary design, conceptual design, and detailed design. Each structural component must be designed, engineered, analyzed, and tested for validations and safety requirements. In this research paper, the wing structure size was based on the third-generation ultralight aircraft category for wing stress analysis.

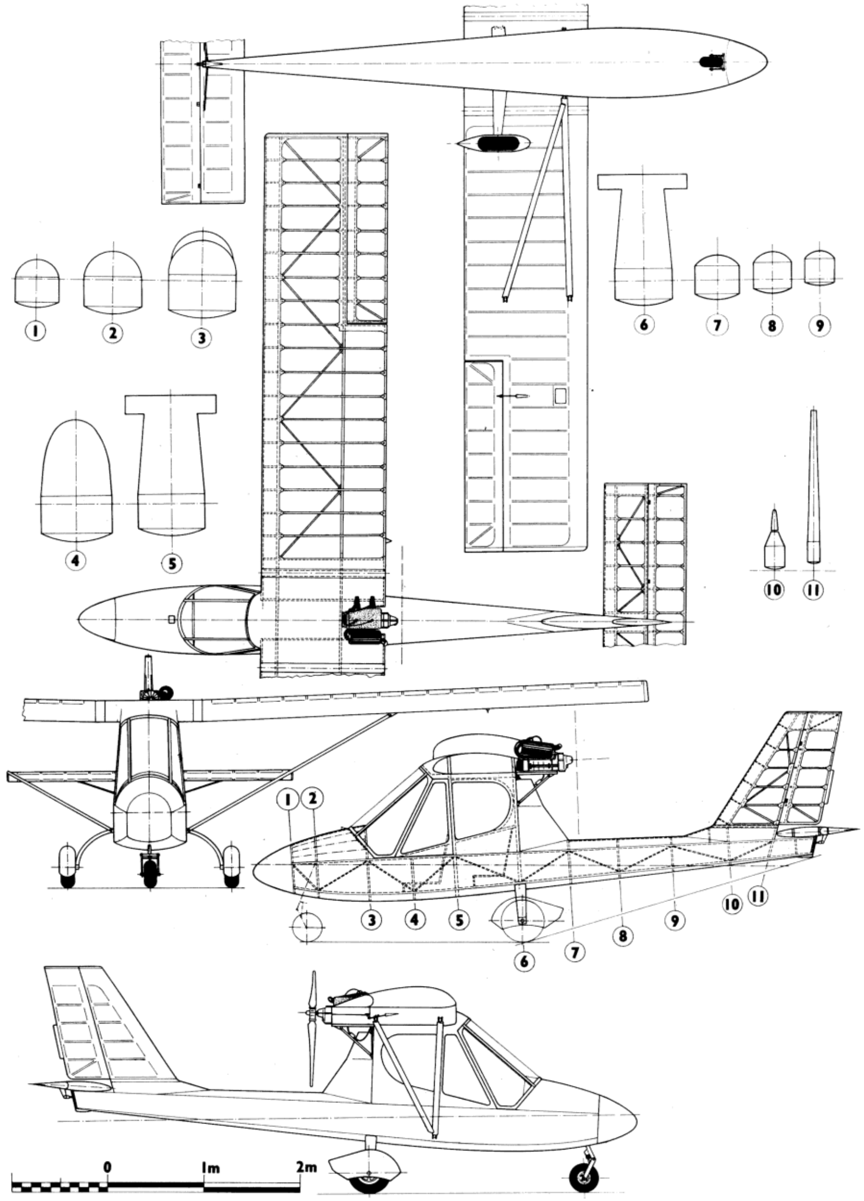

Figure 3: Preview of the Kossak k91 Ultralight Blueprint *(Blueprints, n.d.)*

1.1 PROBLEM STATEMENT

Ultralight aircraft structure integrity is the key to overcome structure failures at any external loads on the ground or in the air and to avoid high maintenance costs. The main wing structure components were the spars and ribs, and they must sustain bending during service, as well as tension, torsion, vibration, and fatigue. For airworthiness based on Federal Aviation Regulations, or FARs, part 103, the structure can:

1. Use an ultimate factor of safety of 1.5 in general.
2. Have no detrimental permanent deformation.
3. Support ultimate loads without failure (FAA, 2007)

Hence, the main constraints for wing materials are stiffness, tensile strength (lower wing structures), compressive strength (upper wing structures), and buckling strength and vibration modes in dynamic analysis. In this research, the objective is to find the factor of safety and flutter speed for the aircraft to enhance safety.

Stress values are one of the main sub-objectives in designing the ultralight's wings and for the findings of the factor of safety. At the first stage in the preliminary design, collective knowledge about aerodynamics, particularly in incompressible flow must be gathered properly to be able to enhance the aerodynamic results to size the wing before going to static stress analysis.

1.2 OBJECTIVES

Besides exploring more on wing stress analysis, this project aimed to obtain the following:

1. Modeling a half-wing structure components of NACA2412 using SolidWorks 2020.
2. Obtaining structural static stress results for structural integrity to fulfill the factor of safety, FOS, FAA-based requirements.
3. Obtaining flutter speed determination based on Aluminum alloy material type 7075-T6 using MATLAB 2019 software.

1.3 SCOPE AND LIMITATIONS

The study was done without access to laboratories due to the lockdown of Covid-19. SolidWorks 2020 and MAT-LAB programs along with Excel Sheet formats were used to conduct the research. Wing stress analysis results were obtained from Solid-Works 2020 using the Split-Line method to split the upper surface of the wing for certain load values. Excel Microsoft sheet, Dr. Halim's sheet format, was used to create a plot of loads. See figure 20. The development of the wing stress analysis for ultra-light airplanes can be considered as a big project which required a lot of processes to be done. Therefore, the project scopes for this are as follow:

1. Studying the wing structural components commonly used in ultralight aircraft.
2. Studying the design requirement to develop a successful wing design for a home-built ultra-light aircraft.
3. Designing and performing static stress and aeroelastic flutter analyses on the wing model using Solid-Works 2020 program.

AIRCRAFT SPECIFICATIONS

Ultralight-aircraft specifications		
Wingspan (m)		8
Semi-span (m)		4
Aircraft Maximum	MTOW (lbs)	452.415
	MLW (lbs)	300
Weight	MZFW (lbs)	253.973

Airfoil Data	Root Airfoil	NACA2412
	Tip Airfoil	NACA2412
	Root Length	1
	Tip Length	1
Skin Thickness		0.5 mm
Spar	Thickness	2 mm
	Position of Front Spars	15%
	Position of Rear Spars	70%
Speed Limitations	MMO	26 m/s
	Cruise Speed	23 m/s

CHAPTER 2

LITERATURE REVIEW

2.1 RELATED STUDIES

2.1.1 Light-Weight Aircraft

The research was done by [L. Zhu, N. Li, P] and [R.N. Childsn] focused on advanced composite materials which contribute effectively to improve stress limitations and factors of safety. The purpose was to reduce the carbon footprint and to improve flight performance such as better acceleration, higher structural strength and stiffness, and better safety performance. All those could be achieved by lightweight composites design.

> *Light-weighting represents an effective way to achieve energy consumption reduction and performance enhancement. This concept has been well accepted and utilized in many industries, especially in aerospace components and system design. Light-weighting design involves the use of advanced lightweight material and numerical structural optimization, enabled by advanced manufacturing methods* (L. Zhu, 2018)

On the other hand, this research paper could contribute to developing techniques on wing stress analysis but not necessarily focusing more on composites.

2.1.2 Ultralight Aircraft

Another research was done by [Yuvaraj S R] and [Subramanyam P], who worked on analyzing ultralight aircraft wings based on different types of materials. The objective was to compare the results obtained for different materials like Al 2024-T3, using CATIA analysis software. From the results, it was concluded which material had better strength properties. This was helpful to understand the flow analysis of wing stress analysis during the research process.

Their structural analysis results were as follows:

Table 2: Static Structural Analysis Results

Material	Deformation (mm)	Elastic Strain-e	Von-Mises Stress (MPa)	Factor of Safety (FOS)
Al 2024-T3	94.609	0.00539	256.46	1.3452
Al 6061-T6	100.38	0.00560	256.46	1.4661
Al 7075-T651	96.456	0.00538	256.46	1.9613
Al 7075+15% Fly Ash	96.563	0.00539	256.46	1.8315

The results above were based on four different types of materials including AL 7075-T6 material which was used in this paper for the analysis. The flutter analysis using the frequency modes from SolidWorks and getting the flutter speed from MATLAB 2019 can be a useful contribution for the development of a safe structured wing.

2.2 CONTRIBUTION

Every research paper contributes to knowledge. Wing structure static and dynamic stress analysis is an important stage in the preliminary design process. The main strategy used in this paper was to split the upper wing surfaces, discretization, into squares so that each obtained a load value. However, an Excel format sheet was vital to develop numerical equations, more specifically, polynomials to represent the chord-wise lift distribution as well as span-wise. That method was simplified and developed with the help of Dr. Halim. The contribution to “add-here” was to simplify the wing structure of an ultralight-aircraft analysis, but not necessarily for larger fixed-wing airplanes. Static stress, strain, displacement, and modal analysis results of the wing were obtained using SolidWorks 2020, while MATLAB 2019 software program was used to identify the flutter speed at which the ultralight-aircraft must not reach for safety.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction:

Designing the ultralight aircraft's wing was an iterative process which, given the numerous iterative calculations that need to be performed, necessitates the use of a computer and SolidWorks 2020 software. Several wing design programs exist and were not freely available with full support, such as ANSYS 2020 R2, which was a student version with limited features and numbers of elements. Excel Sheets were created to analyze the static loads of the wing using combinations of parabolic equations and the Schrenk approximation method for lift distributions.

SolidWorks 2020 program was used later, and the wing model was modified to carry the loads based on a discretized upper surface of the wing. The static stress analysis was performed, and results were obtained. While determining the geometry of the wing due to aerodynamic efficiency as a key part of the process, it is only a small part of the design of a propeller. SolidWorks 2020 helped to calculate the reaction forces based on the distribution of lift loads.

WING'S GEOMETRICAL MODELING ESTABLISHMENT

3.1.1 Airfoil Selection:

The most common source for airfoil designs was from National Advisory Committee for Aeronautics. NACA 2412 was the base airfoil to the wing design of the cross-sectional ribs of the wing's structural components. The spars' thickness and locations were designed within the airfoil profile in Solid-Works 2020. Thicknesses were constant along the wingspan to make it easier for the analysis and to avoid tedious work.

Furthermore, the NACA 2412 airfoil is part of the NACA 4-digit series of airfoil classifications. The four digits are determined by the characteristics of the airfoil based on the following:

1. The first digit describes the maximum camber as a percent of the chord.
2. The second digit describes the locations of that maximum camber measured from the leading edge in percent of the chord.
3. The last two digits describe the maximum thickness of the airfoil in percent of the chord.

With all percentages given in respect to the length of the chord, the classification of the NACA2412 determines that the airfoil has a maximum camber of 2% located at 40% from the leading edge, with a maximum thickness of 12% (Dr. John Matsson, 2016).

3.1.2 Taper Ratio:

The taper ratio is simply defined as the tip chord length divided by the root chord length, respectively. λ is usually less than one. For less complexity, the taper ratio was set to be equal to 1.

$$\lambda = \frac{C_{tip}}{C_{root}} \tag{3.1}$$

3.1.3 Wing Lift and Lift Coefficient's Slope:

This is for an incompressible flow situation where we use a high-aspect-ratio formula for the slope or a small aspect ratio formula.

$$a = \frac{a_o}{1 + \left(\frac{a_o}{pi * e * AR}\right)} \qquad (Slope\ for\ 3D\ Wing); \tag{3.2}$$

$$C_L = a * (\alpha_{AoA} - \alpha_{CL0}) \tag{3.3}$$

$$L = \frac{1}{2} * \rho_{sea_{level}} * V^2 * S * C_L \tag{3.4}$$

3.1.4 **Flight Envelope V-n Diagram Construction:**

After getting our lift coefficient, C_L for the wing and the dynamic pressure, n-factors versus equivalent velocities were calculated by coding in MAT-LAB 2019 to generate our V-n Diagram. Furthermore, the operating flight strength of an airplane is presented in the form of V-g or V-n diagrams, where the "V" denotes airspeed and the "g", or the "n" denotes load factor. A pilot might find a Vg diagram in the flight manual if he is flying a high-performance fighter. The V-g diagram leads pilots to corner speed and that allows them to extract maximum performance from aircraft without breaking it. The operating flight strength limitations of an airplane are presented in the form of a V-n or V-g diagram. This chart is usually included in the aircraft flight handbook in the section dealing with operating limitations.

A typical v-n diagram looks like the figure below.

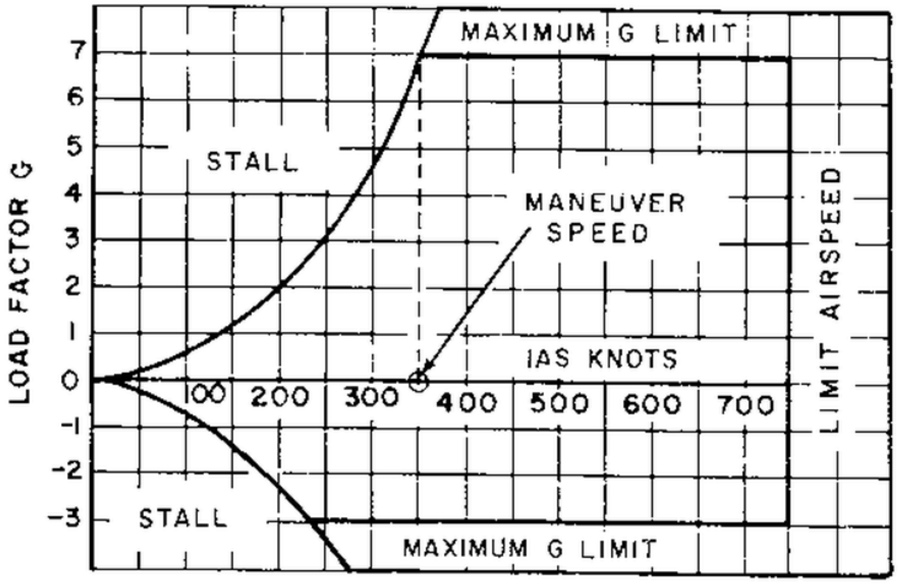

Figure 4: A typical V-n diagram showing the flight's envelop limits (Ref.)

Based on the Federal Aviation Administration, FAA, the airworthiness requirements usually specify that gust loads shall be calculated at certain combinations of gust and flight speed. The equations for the gust load factor in the above analysis show that *n* is proportional to aircraft speed for a given gust velocity.

$$n = \frac{L}{W} = q_{\infty} * S * \frac{C_{L_{max}}}{W} \tag{3.5}$$

$$n = (q_{\infty} * \frac{C_{L_{max}}}{\left(\frac{W}{S}\right)}) \tag{3.6}$$

$$n = \frac{1}{2} * \rho_{\infty} * \ (V_{Stall})^2 * \frac{C_{L_{max}}}{\frac{\mathrm{W}}{\mathrm{S}}} \tag{3.7}$$

Therefore, from the equations above, the gust-envelope was plotted using MAT-LAB 2019 software to form the V-n Diagram. The gust speeds ± $U1$, ± $U2$, and ± $U3$ are high, medium, and low-velocity gusts, respectively. Cut-offs occur at points where the lines corresponding to each gust velocity meet specific aircraft speeds. For example, A and F denote speeds at which a gust of velocity ± $U1$ would stall the wing, see figure 9. The lift coefficient–incidence curve is, as we noted in connection with the flight envelope, affected by compressibility and therefore altitude so that a series of gust envelopes should be drawn for different altitudes. An additional variable in the equations for the gust load factor is the wing loading *w*. Further gust envelopes should therefore be drawn to represent different conditions of aircraft loading.

After the basic V-n diagram and gust V-n diagram are plotted, the combined V-n diagram can be shaped to visualize the flight envelope for the ultralight aircraft. If the ultralight airplane flies beyond the structural limit, a structural failure will occur. Thus, flight envelope establishment was crucial to ensure airworthiness.

3.1.5 **RELATED PARAMETERS**

Chord length and wingspan were important design parameters because they influence the aerodynamic lift from the relationship given in equation (3.4). The lift distribution over the wing was then calculated using the Schrenk approximation distribution. Another important parameter is the velocity: as the speed increases, the lift increases. Thus, we based our research on two different velocities to compare the static analysis results for structure validations.

3.1.6 **MATERIAL SELECTION**

AA7075-T6 has been used as an airframe material since the 1940s because of its ultimate tensile strength of 570 MPa and low price. However, the susceptibility to corrosion of this alloy reduced the life of the airframe components, which has led to its replacement by newAA7xxx series alloys in many applications.

Table 3: AL 7075-T6 (SN) Properties from SolidWorks 2020:

Property	Value	Units
Elastic Modulus	72000	$\frac{N}{mm^2}$
Poisson's Ratio	0.33	-
Shear Modulus	26900	$\frac{N}{mm^2}$
Mass Density	2810	$\frac{kg}{m^3}$
Tensile Strength	570	$\frac{N}{mm^2}$
Yield Strength	505	$\frac{N}{mm^2}$

3.1.7 WING MODELING

At this stage of the study, all structural parts of the aircraft will be modeled using SolidWorks 2020 program.

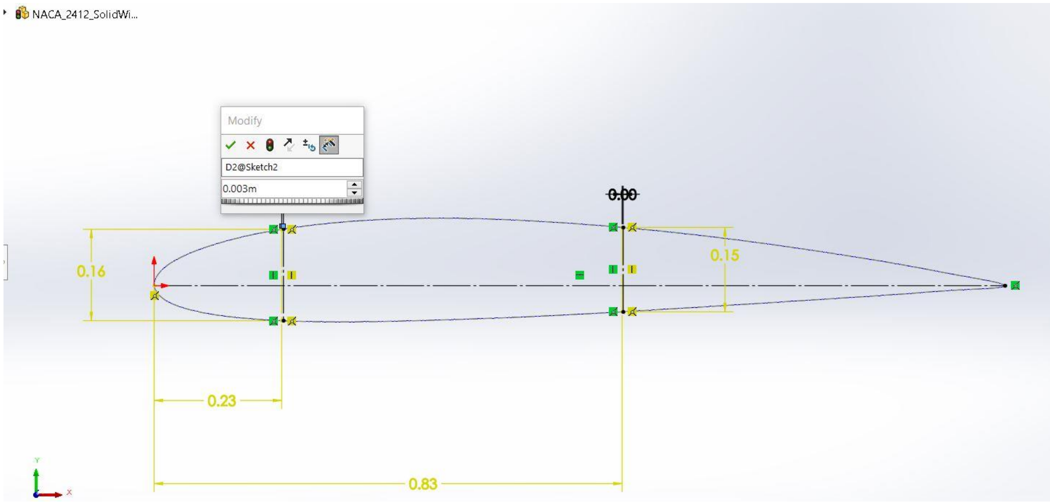

Figure 5: Early Stage of Plotting NACA 2412 Coordinates and Dimensions (SolidWorks 2020)

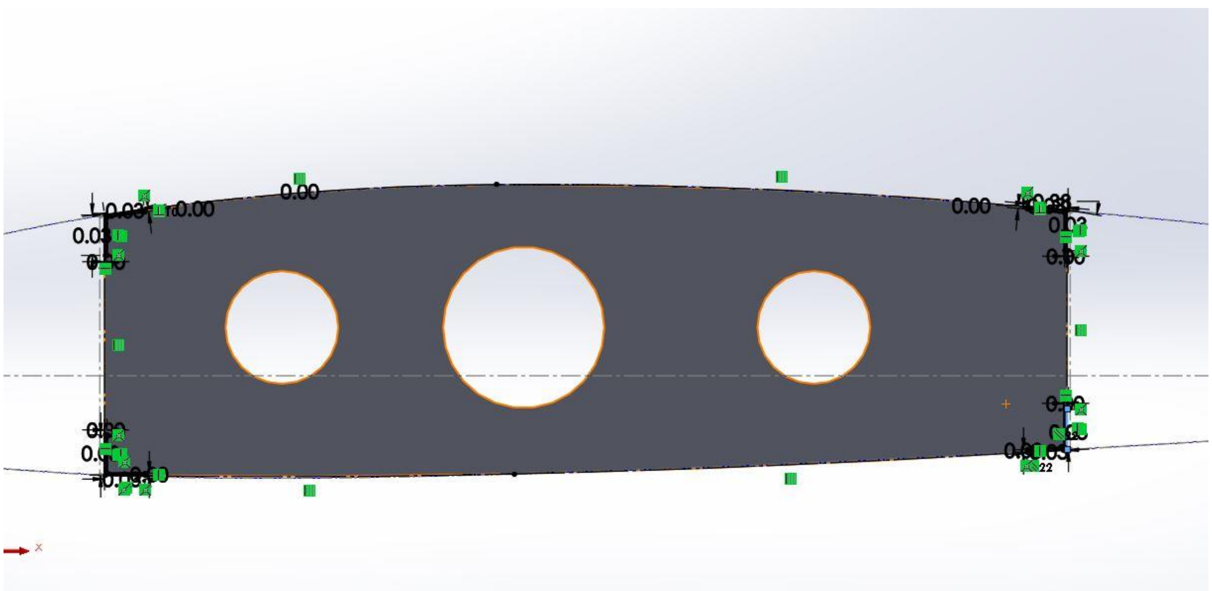

Figure 6: Extrusion of the Mid-Rib using SolidWorks 2020

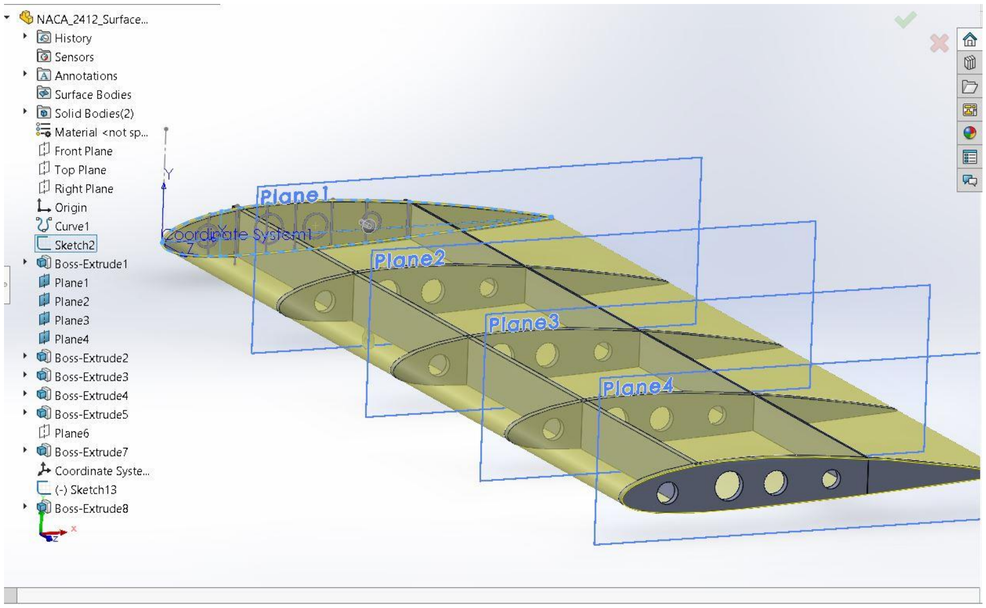

Figure 7: Preview of the Wing Structural Components (SolidWorks 2020)

3.1.8 **V-n Diagram Establishment:**

Each airplane has its V-n diagram, a flight envelope, with specific V's and n's. The flight operating strength of the ultralight airplane is presented on a graph whose horizontal scale is airspeed (V) and the vertical scale is load factor (n). A change in design parameters such as the wingspan will cause changes to the operating limits.

Starting with wing loading,

$$\frac{W}{S} = \frac{Gross\ Weight}{Wing\ Area} \tag{3.8}$$

$$\frac{W}{S} = 3.7734 \frac{lbs}{ft^2}$$

Wing Area,

$$S = \frac{487.397}{3.7734} * \frac{lbs}{\frac{lbs}{ft^2}} = 129.167\ ft^2$$

That is the actual area of my ultralight airplane wing design. Then, the wingspan can be calculated as follows.

$$b = \sqrt{(S * AR)} \tag{3.9}$$

$$b = \sqrt{(129.167 * 5.33)}$$

$$b = 7.997952 \sim 8\ meters$$

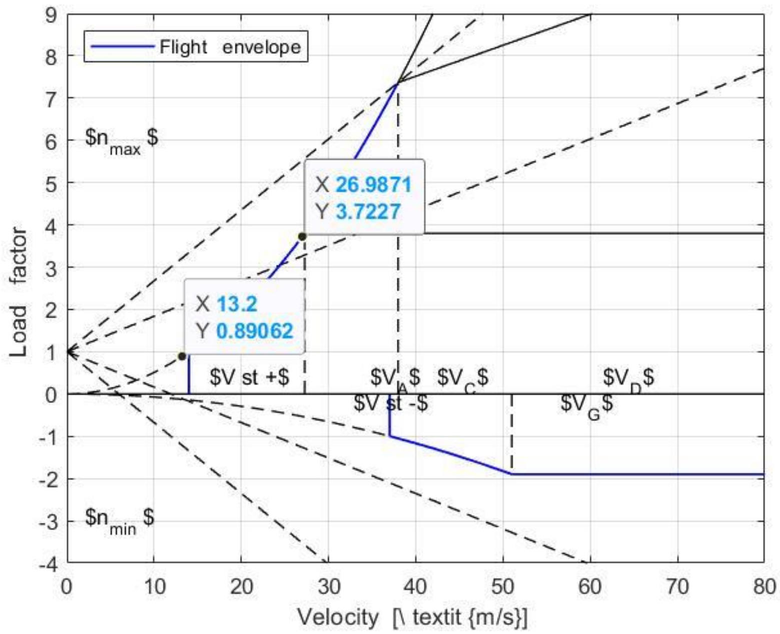

Figure 8: V-n Diagram shows the stall velocities: positive and negative Vs stall, and Maximum Velocity (MAT-LAB 2019)

In figure 8, the important outputs to consider from the flight envelope were as followed: the positive direction, the stall velocity was found to be about 13 m/s. The maximum velocity was about 27 m/s. Those can be modified based on the design requirements and desired flight envelope of the ultralight airplane.

3.1.9 **Meshing**

The meshing process is the process where the program subdivides the model into small elements which are connected at a common point. In analyzing any engineering design, the meshing process is considered one of the most complicated steps to be completed. An imperfect meshing process will influence the effectiveness and precision of the result analysis. The automatic meshing in the software generates a mesh based on a global element size, tolerance, and local mesh control specifications. Mesh control is used to specify different quantities of elements for components, faces, edges, and vertices.

There are three types of meshing elements available in SOLIDWORKS software. The type of This element consists of solid elements, shell elements, and beams elements. In this project, the 3D tetrahedral solid elements will be used. The solid elements were chosen because it is naturally suitable for the engineering designs which are considered as bulky models. See table 4 and figure 9 for mesh details.

Table 4: Mesh Information Details (SolidWorks 2020)

Total Nodes	46575
Total Elements	27884
Maximum Aspect Ratio	2.1219e+05
% of elements with Aspect Ratio < 3	0.258
Percentage of elements with Aspect Ratio > 10	98.8

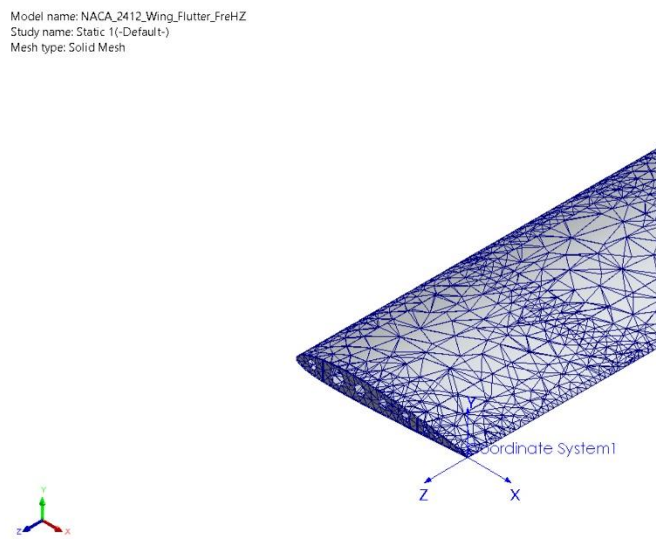

Figure 9: Preview of the Mesh of* the *wing before running the Stress Analysis

3.1.10 **Von Mises Stress**

In the structural design, the different components may be experiencing different types of forces and moments. Depending on the material used by the member and the stress applied to it, the member may fail if the stress exceeds the elastic limit. To validate whether the structure fails or not, Von Mises Stress or equivalent stress is a value used to determine either the material selected will experience failure or not after some loads or forces apply to the structure. Based on the Von Mises yield criterion, the structure will fail if the value of the equivalent stress of a material under load is greater or equal to the yield strength limit, which was 505 MPa. Von Mises stress concept is from the distortion energy failure theory where it is the comparison between two kinds of energies which are the distortion energy in the actual case and the distortion energy in a simple tension case at the time of failure.

The yielding will occur in a body if the components of stress acting on it are greater than the Von Mises criterion. The mathematical derivation is as follow:

Based on Cauchy stress tensor

$$\frac{1}{6}[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6({\sigma_{12}}^2+{\sigma_{23}}^2+{\sigma_{13}}^2)] = k^2 \quad (3.10)$$

Where,

$k =$ Constant defined through experiment

$\sigma =$ Stress tensor

The above expression reduces to:

$$\frac{{\sigma_y}^2}{3} = k^2 \quad (3.11)$$

If σ_y reaches the simple tension elastic limit, S_y. Then the above expression becomes

$$\frac{{S_y}^2}{3} = k^2 \quad (3.12)$$

Substitute into the first expression

$$\frac{1}{6}[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6({\sigma_{12}}^2+{\sigma_{23}}^2+{\sigma_{13}}^2)] = \frac{{S_y}^2}{3} \quad (3.13)$$

Finally

$$\sqrt{\frac{(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6({\sigma_{12}}^2+{\sigma_{23}}^2+{\sigma_{13}}^2)}{2}} = S_y \quad (3.14)$$

The Von-Mises stress, σ_v, is defined as

$$\sigma_v{}^2 = 3k^2 \tag{3.15}$$

Thus, the Von Mises yield criteria also commonly written as

$$\sigma_v \geq S_y \tag{3.16}$$

3.1.11 **Principal Stress**

Principal stress is defined as normal stress which is calculated at an angle when the shear stress is considered as zero. The normal stress can be obtained for maximum and minimum values. The maximum value of normal stress is known as major principal stress and the minimum value of normal stress is known as minor principal stress. The main formulas for maximum and minimum principal stresses are shown below.

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}{}^2} \tag{3.17}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}{}^2} \tag{3.18}$$

Theoretical Method

3.1.12 **Critical Stress**

Buckling usually may happen for the structure experiencing compressive loads. Critical stress is calculated to identify the compressive buckling stress and shear buckling stress. The main formula for compressive buckling stress and shear buckling stress is shown below.

$$\sigma_{CR} = \frac{k_\sigma \pi^2 E}{12(1-v^2)} \left(\frac{t}{b}\right)^2 \quad (3.19)$$

Where,

σ_{CR} = Compressive buckling stress

k_σ =Compressive buckling coefficient

E =Young Modulus

v =Poisson's Ratio

t =Thickness

b =Width

The graphs: (a) and (b) below show how to predict the compressive buckling coefficient and shear buckling coefficient of the wing skin panel between the spars and ribs.

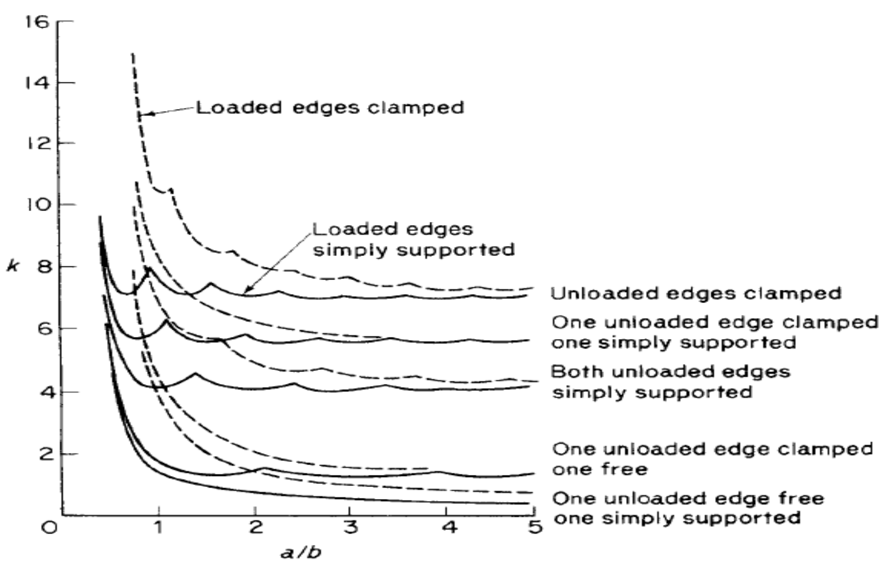

Figure 10: K value graph *(Megson, 2007)*

(a)