بسم الله الرحمن الرحيم

Sudan University of Science and Technology

Faculty of Engineering

Aeronautical Engineering Department

Fluid Structure Interaction for Light Aircraft Wing (SAFAT 03)

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science. (BSc Honor)

By:

1. Faris Ahmed Mohammed Al-hadi
2. Mosab Adel Mohammed Ahmed

Supervised by:

Researcher. Mohammed Mahdi

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الآية

"أَمْ حَسِبْتُمْ أَن تَدْخُلُوا الْجَنَّةَ وَلَمَّا يَأْتِكُم مَّثَلُ الَّذِينَ خَلَوْا مِن قَبْلِكُم ۖ مَّسَّتْهُمُ الْبَأْسَاءُ وَالضَّرَّاءُ وَزُلْزِلُوا حَتَّىٰ يَقُولَ الرَّسُولُ وَالَّذِينَ آمَنُوا مَعَهُ مَتَىٰ نَصْرُ اللَّهِ ۗ أَلَا إِنَّ نَصْرَ اللَّهِ قَرِيبٌ"

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Abstract

This project is made to study the fluid structure interaction for light aircraft wing structure (SAFAT 03 wing structure) that was drawn by CATIA software; in order to know if the requirements of certification are being satisfied to ensure the freedom of aeroelasticity problem such as flutter and divergence.

Galerkin energy method utilized to calculate the flutter and divergence speed and a MATLAB code used in order to calculate the flutter speed

The fluid structure interaction approach has been used in ANSYS, the problem setup in ANSYS environment and tested using a typical wing configuration, but due to the complexity of SAFAT-03 wing structural components and the limitation of computing platform the results not obtained using ANSYS.

التجريد

تم عمل هذا المشروع لدراسه FSI لتركيب جناح الطائرة الخفيفه (تركيب جناح صافات 03) الذي رُسم عن طريق برنامج ال CATIA بصدد معرفه تحقيق متطلبات الشهاده لضمان خلو الجناح من ظواهر المرونه الهوائيه مثل الرفرفه والاتساع.

استخدمت طريقه Galerkin energy وطُبّق كود عن طريق برنامج ال MATLAB لحساب سرعه الرفرفه وتم استخدام حسابات نظريه بالمعادلات لحساب سرعتي الاتساع و الرفرفه .

يجب استخدام FSIعن طريق ال ANSYS لمقارنه او تأييد النتائج. لكن واجهتنا بعض المشاكل التي تعيق انسياب المشروع ولاتضمن سريانه في المجرى الصحيح مثل عدم توفر supercomputer يُمَكِنُنا من حساب سرعتي الرفرفه والاتساع. وكذلك تعقيد البنية الهيكلية لجناح الطائرة صافات-3.

Acknowledgment

Thanks to Allah firstly who give us an ability to do this really hard work by his mediumistic power and appreciate the massive effort from our seniors,

also special thanks to our college students and persons in this field (aeronautical field) and we also appreciate the instructions from our supervisor.

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List of symbols

$\bar{q}$	Dynamic Pressure Ratio
q	Dynamic Pressure
q_D	Divergence Dynamic Pressure
ρ	Density
V_1	Velocity without scale
V_2	Scaled Velocity
R	Scale Factor
U_{SUM}	Total Displacement
$V_{divergence}$	Divergence Speed
GJ	Torsion Stiffness
e	Distance between Aerodynamic Center and Elastic Center
A	Lift Curve Slope
Θ	Deflection Angle
$\ddot{h}$	Linear Acceleration
B	Semi Chord
x_θ	The difference between e and a
$\ddot{\theta}$	Angular Acceleration
k_h	Linear Stiffness
H	Linear Distance
I_P	Polar Inertia
k_θ	Angular Stiffness
ρ_∞	Freestream Density
U	Relative Velocity
w_h	Kappa Frequency (Bending Frequency)
w_θ	Theta Frequency (Torsion Frequency)
V_{div}	Dive Speed
V_{cruise}	Cruise Speed

List of abbreviation

C	Chord Length
L	Semi Wing Span
M	Moment
M	Mass
Max	Maximum
Min	Minimum
T	Torque

Chapter One: Introduction

1.1 Overview

Fluid-structure interaction (FSI) is interacting of solid structures with an internal or surrounding fluid flow. FSI problems play prominent roles in many scientific and engineering fields.

Fluid-structure interaction (FSI) occurs when a fluid interacts with a solid structure, exerting pressure on it, which may cause deformation in the structure. [1]

1.2 Problem Statement

To get type certification of SAFAT® 03 it should be free from flutter , divergence and aileron reversal and also the structure must be able to resist the structural problems during flight envelope [2],So Verification of SAFAT® 03 wing structure is important.

1.3 Proposed Solution

Structural and aero elastic Analysis of the wing structure by using analytical and computation methods.

1.4 Objectives

1. Examine of wing deformation
2. Estimate the aero elasticity specification (divergence, flutter)

1.5 Methodology

3D wing model drawn as CAD format by CATIA application, the model Modified to be suitable for CFD, the modified model entered into CFD, to solve it as unsteady aerodynamic, the internal structure of the wing and its materials defined, and then the structure model entered to mechanical part, to solve it as transient FEM**.**

The pressure distribution transferred from CFD to structural part. ANSYS® System coupling used to return the deformed mesh to CFD to solve it again, in addition to repeat this process.

This will be repeated at 1.2*V_{dive}, divergence and flutter speeds, then the results Arranged in the tables and plotted on graphs, to evaluate it.

1.6 Thesis Outline

Chapter two studied literature review, chapter three deal with calculations, chapter four showed results and discussion and chapter five take the conclusion, recommendation and future work.

Chapter two: Literature review

"Aeronautical engineering is the science or study of the design of aircraft"[3]. So this requires more regards for the safety, to save the life of the human. So there are more phenomena must take into account. One of this phenomena the aero elasticity.

2.1 Aeroelasticity

" Aeroelasticity is the subject that describes the interaction of aerodynamic, inertia and elastic forces for a flexible structure and the phenomena that can result. "[4] This field of study is summarized most clearly by the classical Collar aero elastic triangle in figure 1

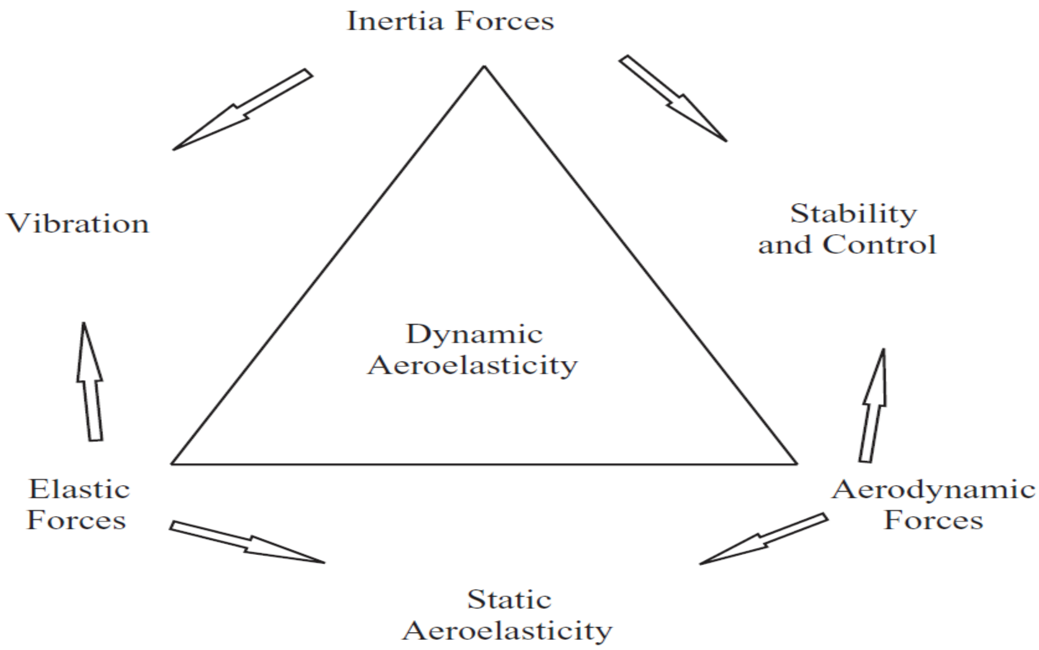


Figure 1: Collar's aeroelastic triangle. source[4]

- Stability and control (flight mechanics) = Dynamics + Aerodynamics
- Structural vibrations = Dynamics + Solid Mechanics
- Static aeroelasticity = Steady Flow Aerodynamics + Solid Mechanics

The Aeroelasticity is divided into two class:

The first class Static aeroelasticity involves the interaction of aerodynamic and elastic forces. Such interactions may exhibit divergent tendencies in a too flexible structure, leading to failure, or, in an adequately stiff structure, converge until

a condition of stable equilibrium is reached.[5]

The second class involves the inertia of the structure as well as aerodynamic and elastic forces. Dynamic loading systems, of which gusts are of primary importance, induce oscillations of structural components. If the natural or resonant frequency of the component is in the region of the frequency of the applied loads then the amplitude of the oscillations may diverge, causing failure.[5]

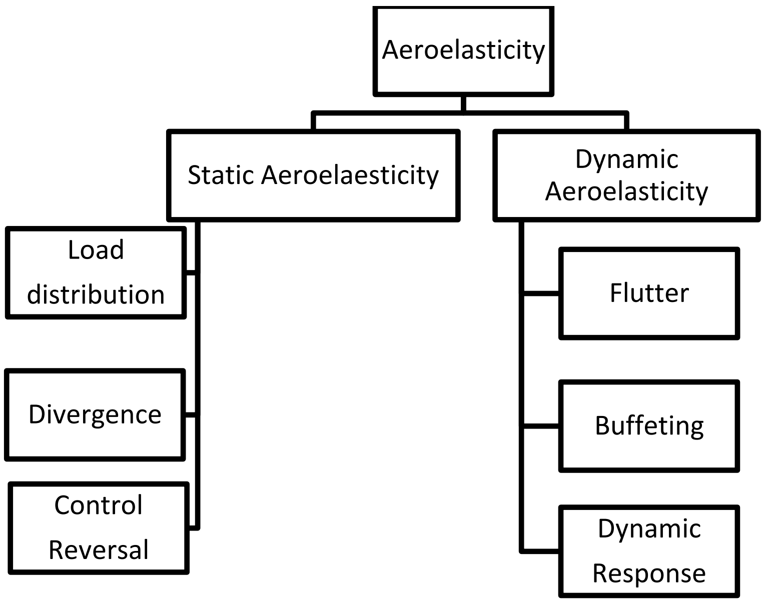


Figure 2: Tree of Aeroelasticity. source[5]

2.1.1 Divergence

Divergence is static instability of a lifting surface of an a/c in flight, at speed called divergence speed, where the elasticity of lifting surface plays an essential role in the instability[6]

$$\bar{q} = \frac{q}{q_D}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots1$$

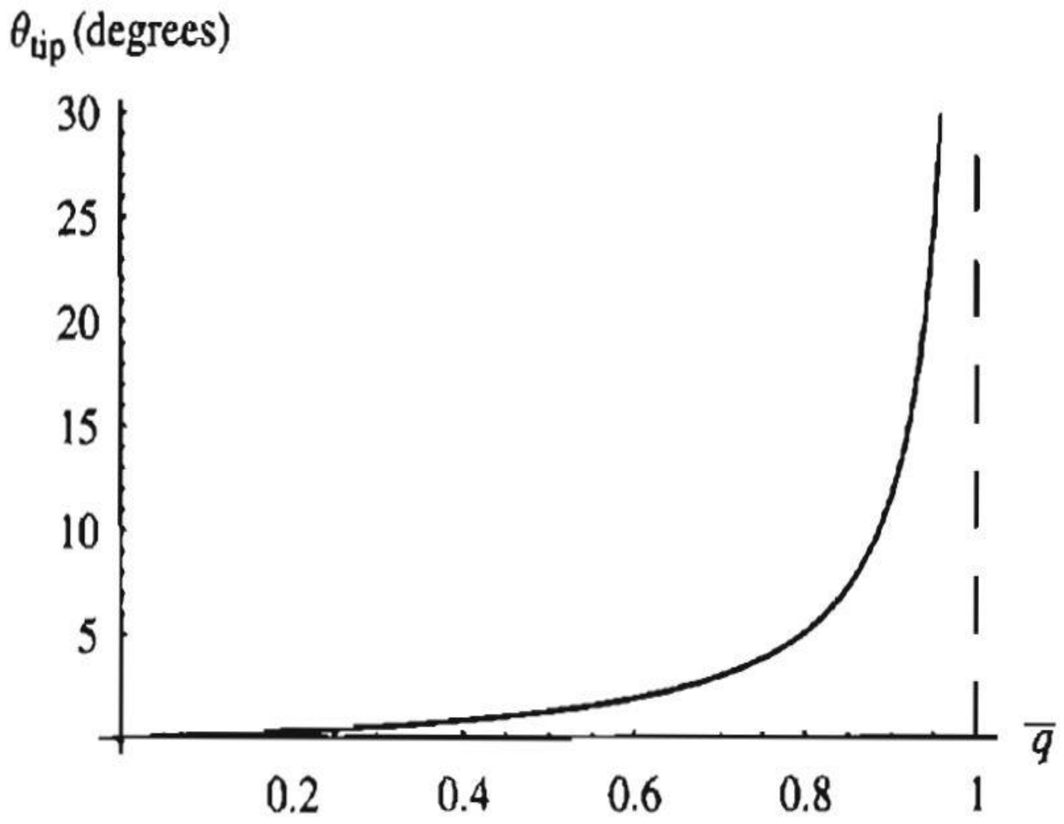


Figure 3: Divergence.   Source[7]

2.1.2 Flutter

Is defined as a dynamic instability of flight vehicle associated with the interaction of aerodynamic, elastic, and inertial forces.[7]

At some critical speed, known as the flutter speed, the structure sustains oscillations following some initial disturbance. Below this speed the oscillations are damped, whereas above it one of the modes becomes negatively damped and (often violent) unstable oscillations occur,[7]

Unless some form of nonlinearity (not considered in detail here) bounds the motion. Flutter can take various forms involving different pairs of interacting modes, e.g. wing bending/torsion, wing torsion/control surface, wing/engine, etc.[4] wing bending/torsion mode which is taken into account.

2.1.3 Torsion and Bending Wing Flutter

This type of flutter occurs when wing bending and torsion mode are coupled.

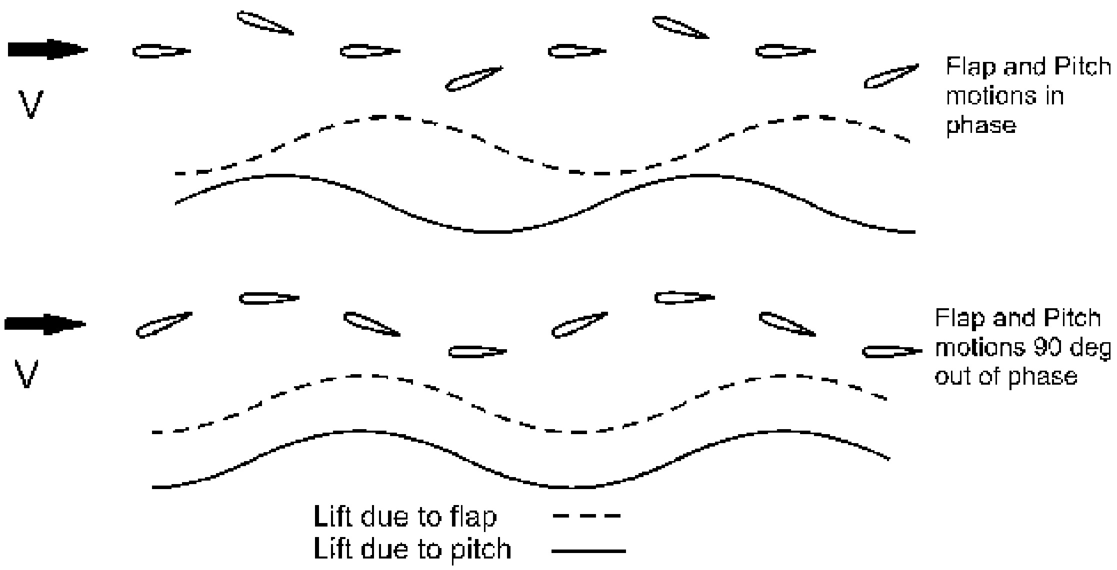


Figure 4: Wing Flutter. Source [4]

$$m(\ddot{h} + bx_\theta\ddot{\theta}) + k_h h = -L \quad \text{……………….……. 2}$$

$$I_P\ddot{\theta} + mbx_\theta\ddot{h} + k_\theta\theta = M_{\frac{1}{4}} + b\left(\frac{1}{2} + a\right)L \quad \text{………. 3}$$

By assuming

$$L = 2\pi\rho_\infty bU^2\theta \quad \text{…………………4}$$

$$M_{\frac{1}{4}} = 0 \quad \text{……………………….....5}$$

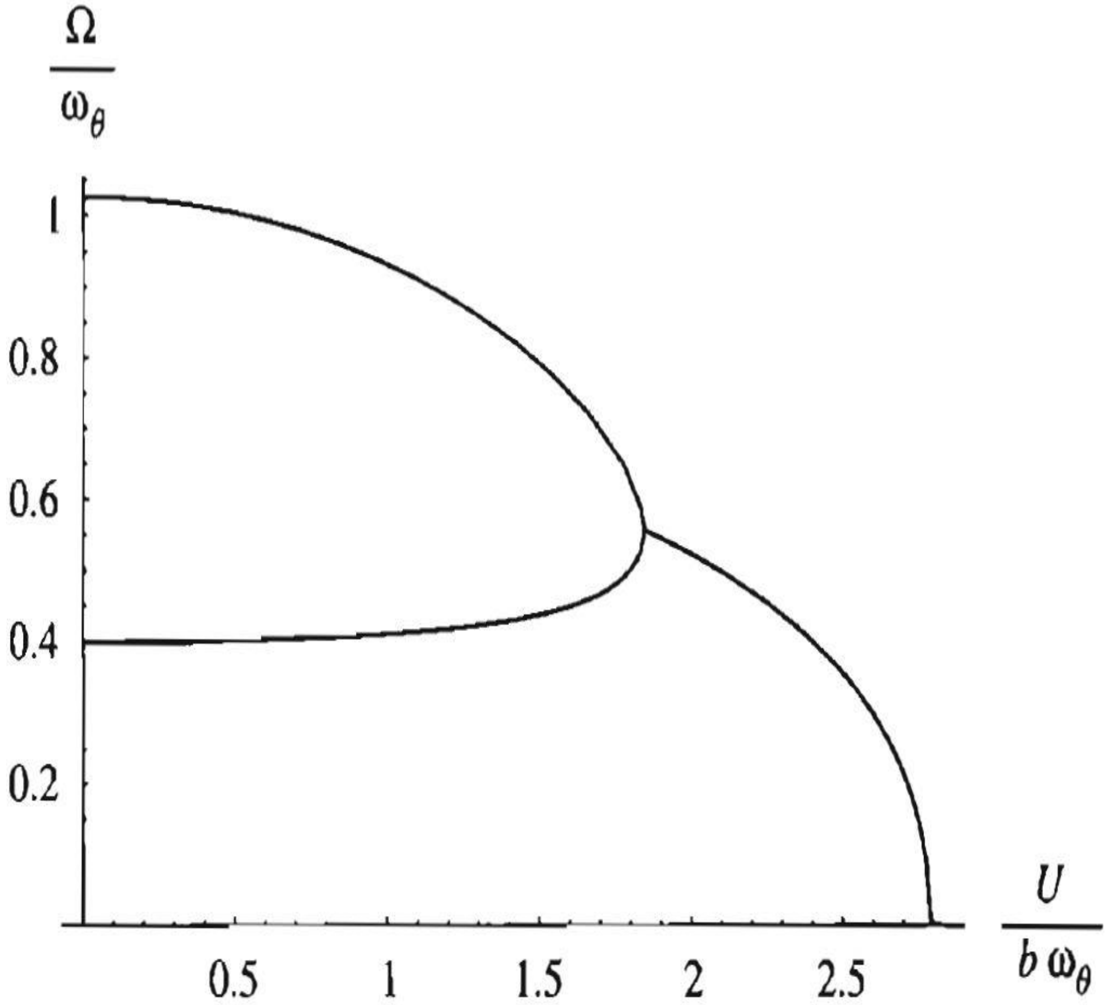
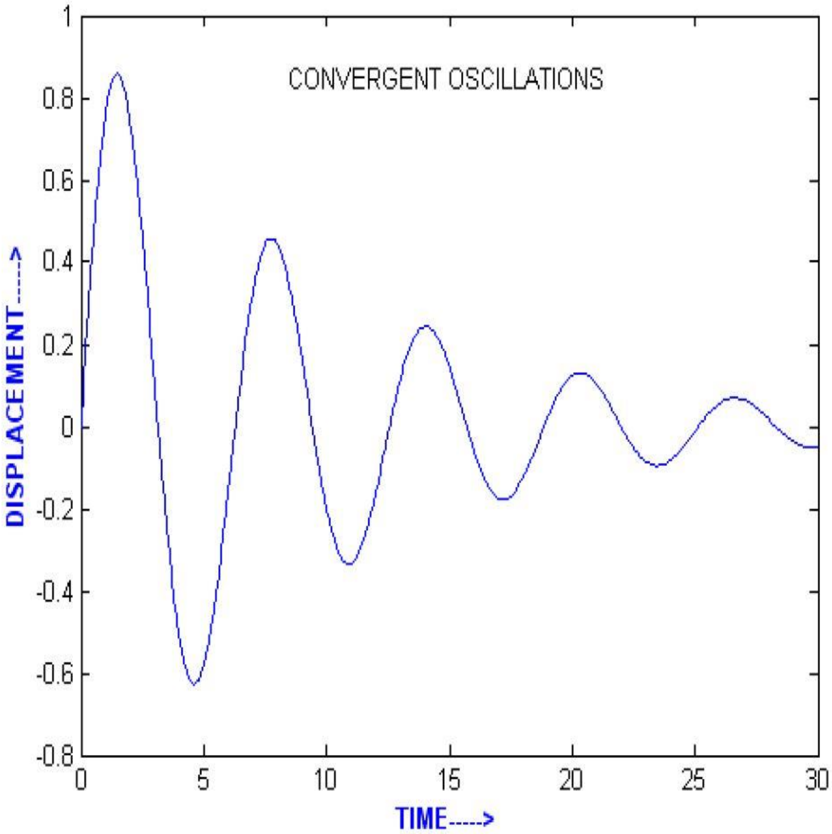


Figure 5: Torsion Frequency Vs Bending Frequency. Source [7]

Flutter occurs at Velocity at which torsion frequency equal the bending frequency.[7]

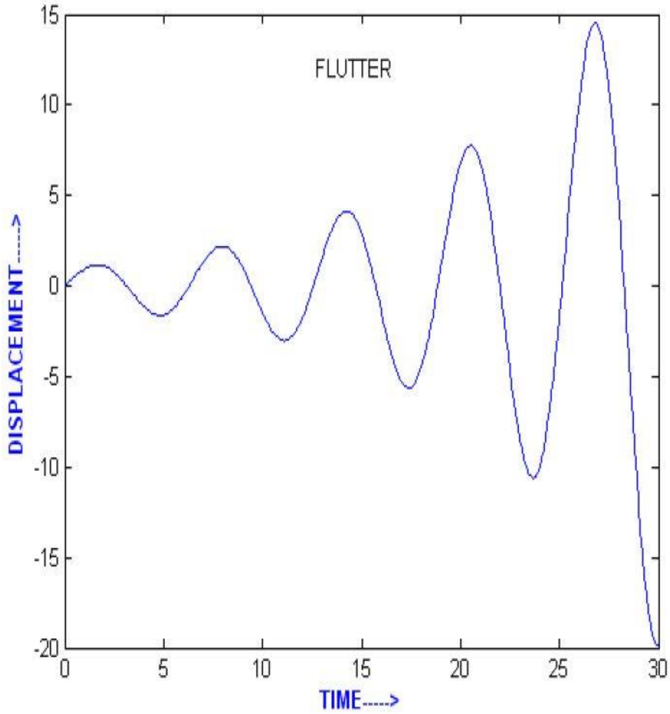
The characteristic behavior of a typical mode that undergoes flutter instability under varying airflow speeds U is shown in Figures 6,7and 8[8]



Stable

$U<U_{cr}$

Figure 6: Damping.   Source[8]



Unstable (Flutter)

$U>U_{cr}$

Figure 7: Oscillation. Source[8]

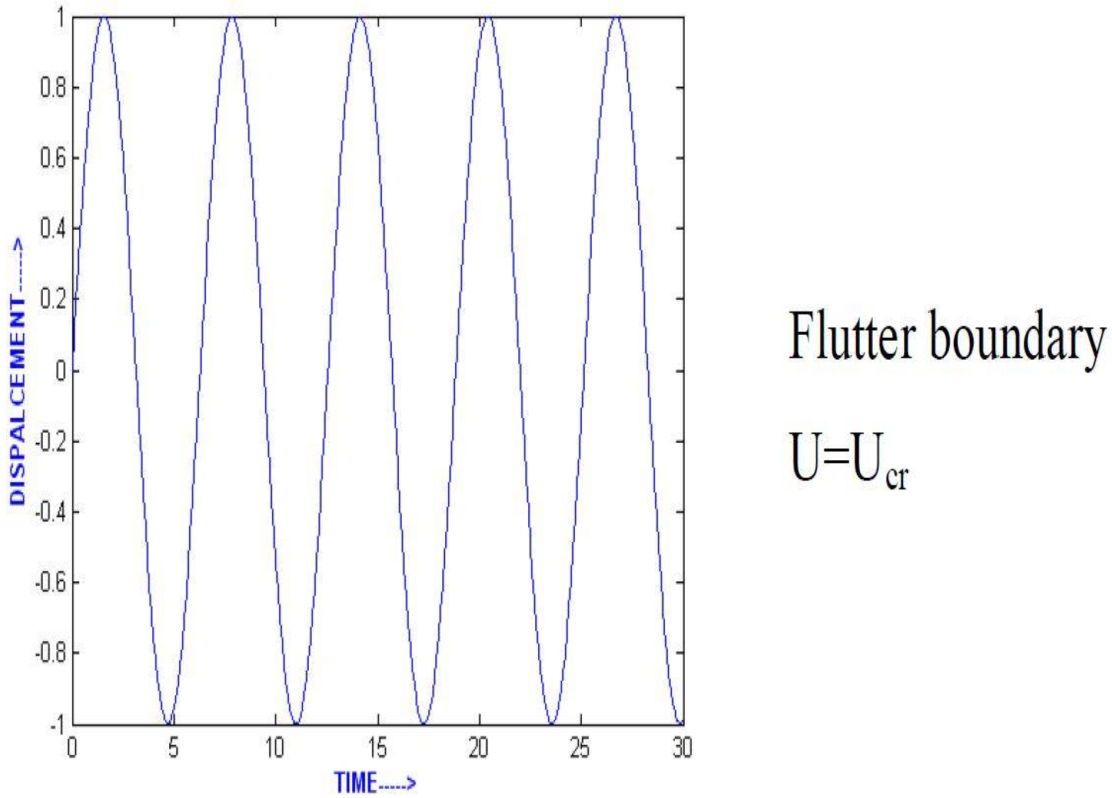


Figure 8 Boundary. source[8]

2.2 Fluid Structure Interaction

Fluid-Structure Interaction (FSI) analysis is an example of a Multiphysics problem where the interaction between two different physics phenomena, done in separate analyses, is taken into account.[9]

From the perspective of the Mechanical application, an FSI analysis consists of performing a structural or thermal analysis in the application, with some of the loads (forces or temperatures, for example) coming from a corresponding fluid analysis or previous CFD analysis. In turn, the results of the mechanical analysis may be used as loads in a fluids analysis. [9]

The interaction between the two analyses typically takes place at the boundaries that the mechanical model shares with the fluids model. These boundaries of interaction are collectively called the fluid-structure interface. It is at this interface where the results of one analysis are passed to the other analysis as loads.[9]

For one specific Multiphysics problem, the structural thermal-stress analysis, an FSI analysis is not always required. If the thermal capabilities of the Mechanical application are sufficient to determine a proper thermal solution, an FSI approach (using separate applications for separate analyses) is not required and the thermal-stress analysis can be done entirely within the Mechanical application.[9]

In the case where the thermal solution requires the specialized capabilities of a CFD analysis, the structural thermal-stress analysis is done using the FSI approach. The CFD analysis is done first, then the calculated temperatures at the fluid-structure interface are applied as loads in the subsequent mechanical analysis.[9]

Typical applications of FSI include:

- Biomedical: drug delivery pumps, intravenous catheters, elastic artery modeling for stent design.
- Aerospace: airfoil flutter and turbine engines.
- Automotive: under-the-hood cooling, HVAC heating/cooling, and heat exchangers.
- Fluid handling: valves, fuel injection components, and pressure regulators.
- Civil engineering: wind and fluid loading of structures.
- Electronics: component cooling.

The Mechanical application supports two types of Fluid-Structure Interaction one-way transfer and two-way transfer.[9]

2.2.1 One-way FSI

In a one-way transfer FSI analysis, the CFD analysis results (forces, temperatures, convection loads, or heat flows) at the fluid-structure interface are transferred to the mechanical model and applied as loads. The subsequently calculated displacements or temperatures at the interface are not transferred back to the CFD analysis.[9]

One-way transfer is appropriate when displacements and temperatures differentials calculated in the Mechanical application are not large enough to have a significant impact on the fluid analysis.[9]

There are four supported applications of a one-way FSI analysis:

- Pressure results from a CFD analysis are input as applied forces in a structural analysis at the fluid-structure interface.
- Temperature results from a heat transfer CFD analysis are input as body loads in a structural analysis to determine the thermally induced displacement and stresses (thermal-stress analysis).
- Convections from a heat transfer CFD analysis are input as convection boundary conditions (film coefficients and bulk temperatures) in a thermal analysis at the fluid-structure interface.
- Temperatures or heat flows from a heat transfer CFD analysis are input as temperature or heat flow boundary conditions in a thermal analysis at the fluid-structure interface.[9]

2.2.2 Two-way FSI

In a two-way transfer FSI analysis, the CFD analysis results (forces, temperatures, heat flows, or heat transfer coefficients and near wall temperatures) at the fluid-structure interface are transferred to the mechanical model and applied as loads. Within the same analysis, the subsequently calculated displacements, temperatures, or heat flows at the fluid-structure interface are transferred back to the CFD analysis.[9]

Two-way transfer is appropriate when displacements and temperature differentials calculated in the Mechanical application are large enough to have a significant impact on the fluid analysis.[9]

Because of the two-way interaction between the two analyses, the analyses are looped through repeatedly until overall equilibrium is reached between the Mechanical application solution and CFD solution.[9]

Two-way FSI is supported between Mechanical and Fluent and Mechanical and CFX. In either case, you set up the static or transient structural portion of the analysis in the Mechanical application, including defining one or more fluid-structure interface boundary conditions. Continuing the analysis in Fluent or CFX, and view the structural results in the Mechanical application.[9]

C.bibin was studied the flutter phenomena of aircraft wing modeled by CATIA at different dynamic condition, ultimate condition was assumed at subsonic cruise speed then study both the structural deformation and flow distribution over wing. The boundary condition was taken from CFD and from this inputs the FEA will solve the structural deformation and stress distribution, in addition to using fluent software to get pressure distribution results. The results have been accurate when it compared with structural result.[10]. But these results can be more accurate by using system coupling.

Later Modeling of the wing of HALE UAV- Morphing Wing (swept& upswept) in CATIA then analyzed for the aerodynamic under the given flight conditions. The pressure distribution resulted from the Fluent (flow) analysis is then applied as a structural load over the wing in ANSYS.

The results are then plotted using MATLAB. As Mahindra Kumar doing that for analyzing the wing flutter, the result of stress have been within the elastic region.[11]

But, if this wing has structural parts, it will give real results, also its better to use ANSYS for plotting the results for more accuracy and must use another method to evaluate the result

2.3 SAFAT 03

SAFAT03 is light aircraft for basic pilot training, glider tow and proficiency flight. It is completely metal aircraft with two seats, low wing aircraft with seats one along second, tricycle with fixed landing gears, with contemporary pilotage’s, navigation’s and communication’s equipment's.[12]

2.3.1 Specifications

Table 1: SAFAT 03 specifications. source[12]

ESTIMATED WEIGHTS	
Maximum Takeoff Weight	1080 kg
Empty Weight	543 kg
FLIGHT CHARACTERISTICS	
Range	800 km
Maximum Speed	215 km/h
Length of takeoff field	268 m
Length of landing field	350 m
Service Ceiling	4000 m
Cruise Speed	185 km/h
Rate of Climb (with 0º flap)	4.6 m/sec
Engine Type	LYCOMING IO-360-B1F with power 180 hp. Propeller: HARTZELL HC-C2Y--1BF/F7666A
Chord Length	1.61895 m
Semi Span Length	3.3266 m

Figure 9: SAFAT 03

2.3.2 SAFAT 03 Wing Structure

Cantilever, rectangular, with main and aux wing spar, rips skin and the integral fuel cell located between them. With NACA 65_2415 [13]

Table 2: Materials used in wing

Spars, Strangers	Aluminum alloy 7075-T6
Skin, Ribs	Aluminum alloy 2024-T3

Table 3: Material Physical properties

	Aluminum alloy 7075-T6	**Aluminum alloy 2024-T3**
Modulus of elasticity	71.7GPa	73.7GPa
Shear Modulus	26.9GPa	28GPa
Poison Ratio	0.3	0.3
Ultimate Tensile Strength	572MPa	483MPa
Tensile Yield Strength	503MPa	345MPa
Density	2.81g/cc	2.78g/cc

Chapter Three: Calculation

This chapter is deal with calculations of flutter and divergence speeds analytically and numerically but also take the geometry drawing and its details (such as meshing) in account.

3.1 CATIA drawing

The wing was drawn by CATIA software, this wing consists of 11 ribs,2 spars (main and front), 8 stringers and skin

Figure 10 is to demonstrate rear rib

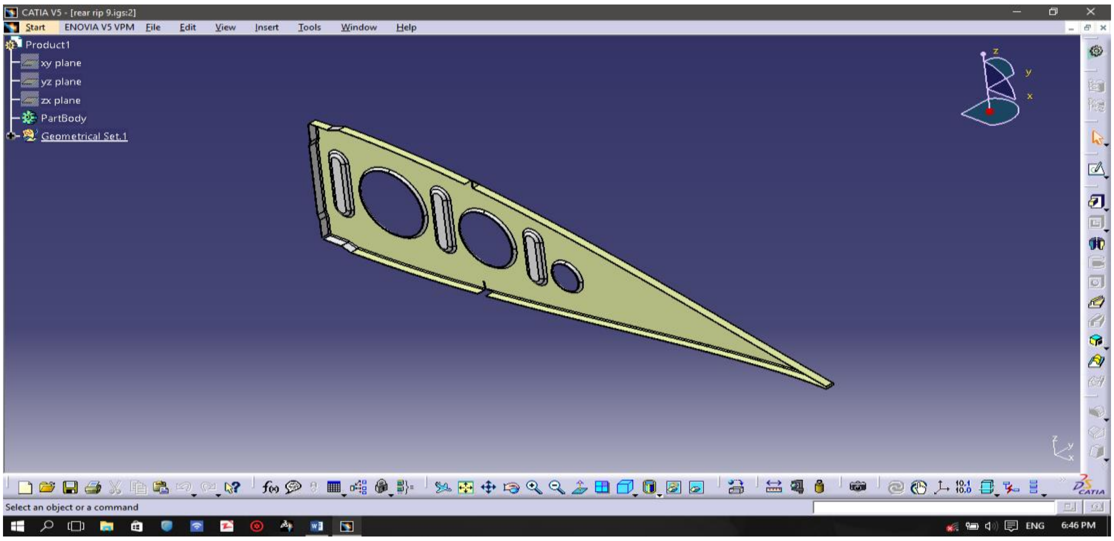


Figure 10: Rear Rib

And the figure 11 demonstrates tip rib

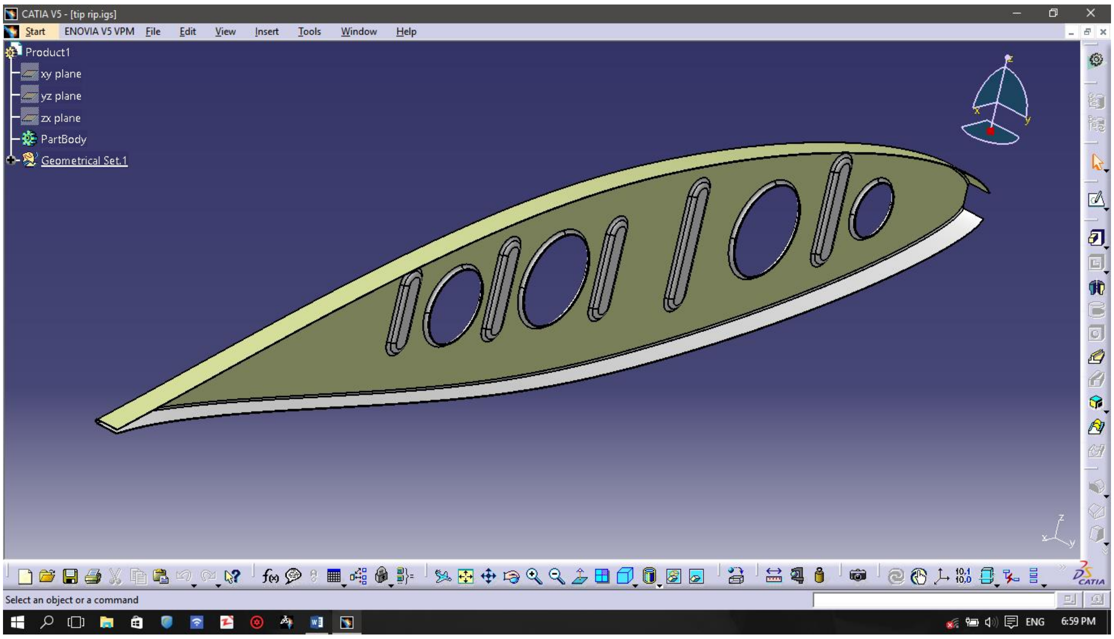


Figure 11: Tip Rib

First the airfoil was imported from dotdat file to CATIA through EXCEL, then determine the dimensions of this part as sketch, after that convert it to solid by web in aerospace sheet metal design option, then surface flange added to it. After that circular section cut out from rib by cut out option with adding flange to it. Then stamp was added to rib surface by surface stamp option.

Finally, joggle added to flange edges by joggle option. And the previous process used to other ribs.

Then the mid rib drawn as shown in figure 12

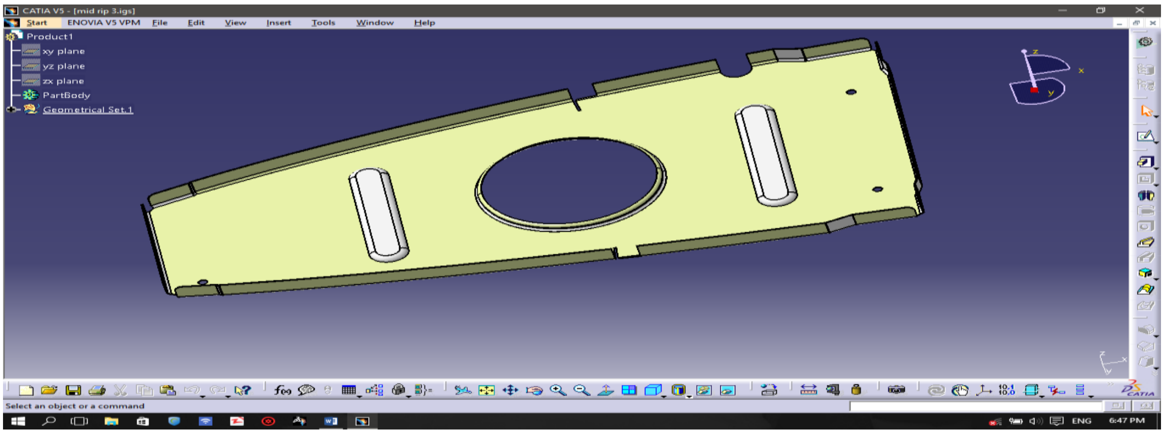


Figure 12: Middle Rib

Then the nose rib was drawn as shown in figure 13

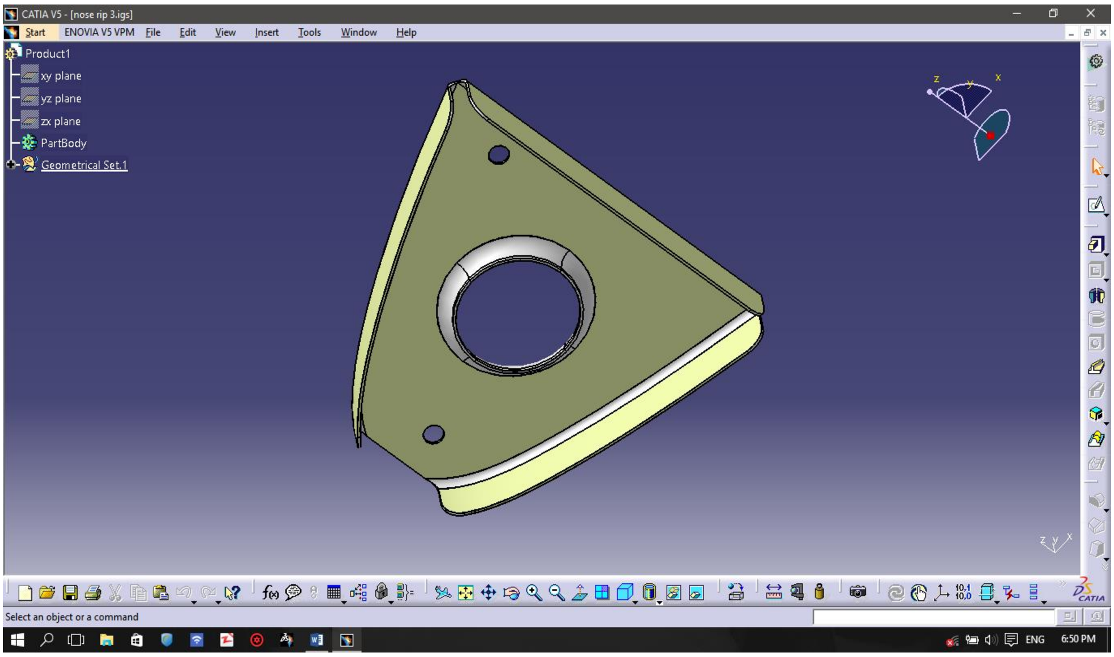


Figure 13: Nose Rib

After that the stringers was drawn as shown in figure 14 below

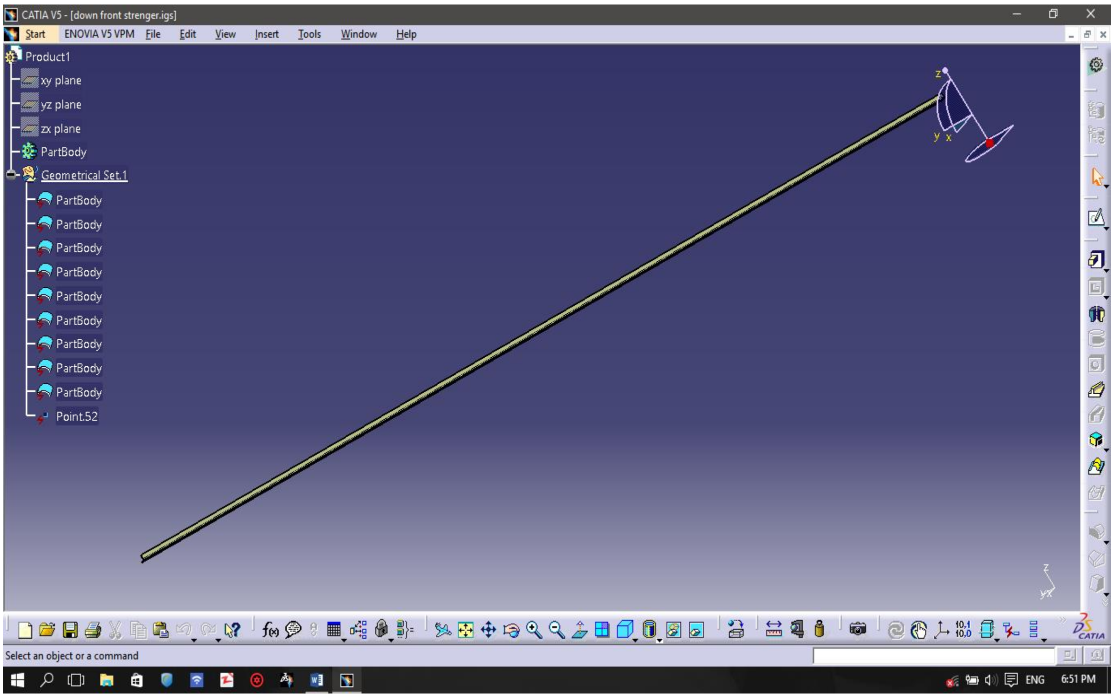


Figure 14: Stringer

First, “L” section was drawn and apply pad to it, then the spar was drawn as shown in figure 15.

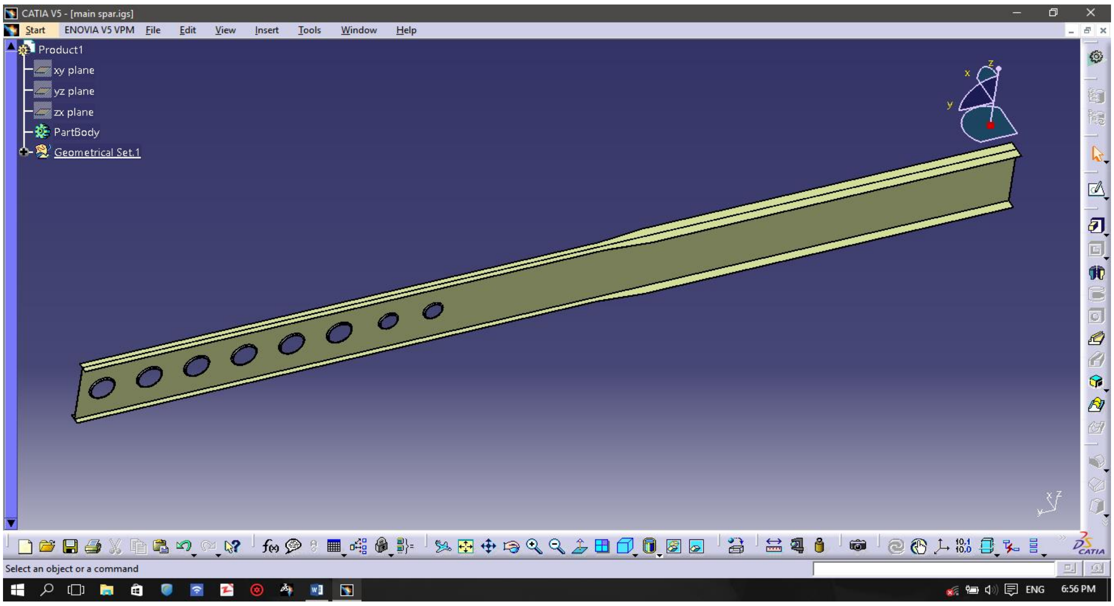


Figure 15: Main Spar

First, the “I” section was drawn and applying pad to it with adding flange for both top and bottom face, then cut out circular section from main spar with adding flange to each circular sections, then the piece between nose rib and spar was drawn as shown in figure 16

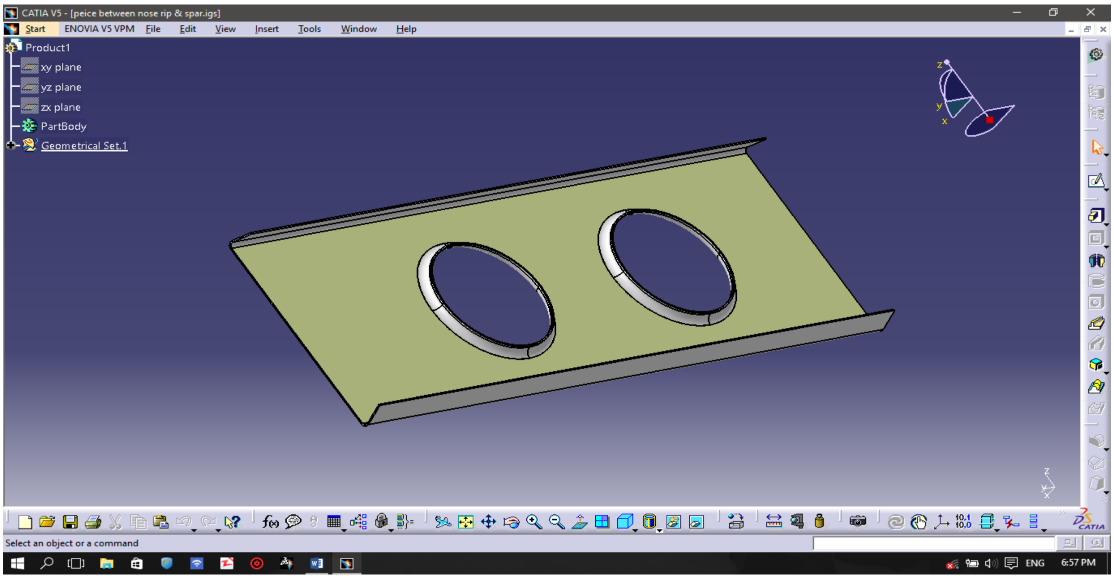


Figure 16: Piece between Nose Rib and Spar

Then all structural items were assembled in one structure as shown in figure 17

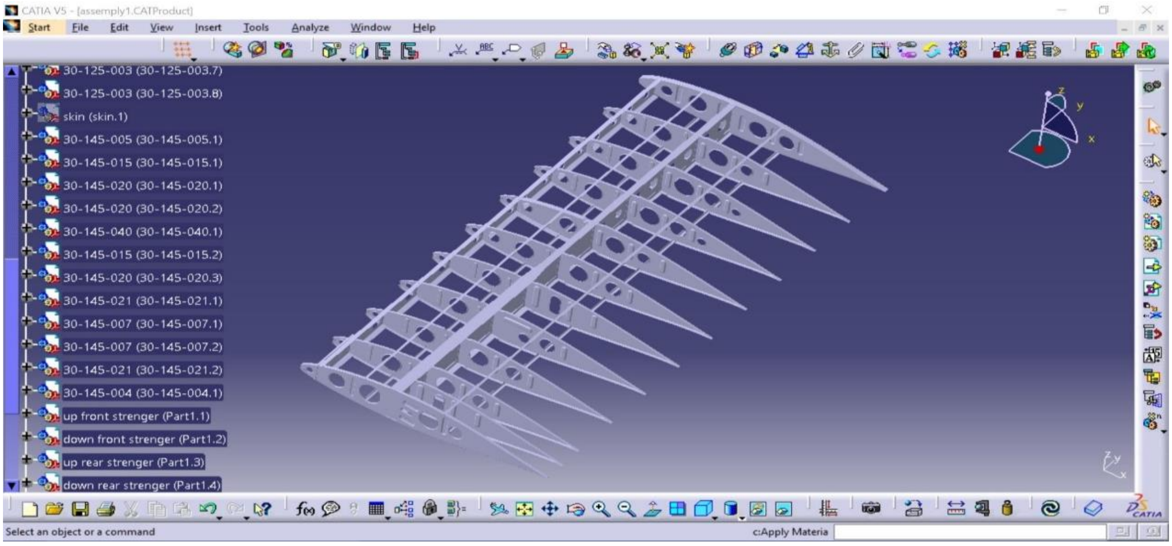


Figure 17: Wing draw without skin

These parts or items were assembled together by offset constrain to demonstrate the spacing between ribs, after that by using quick constrain to connect the surface of the part together. Also manipulation used to move the parts throw and around all axis.

Finally, remove option used to remove the intersection between the parts

lastly, figure 18 is to show wing structure with skin

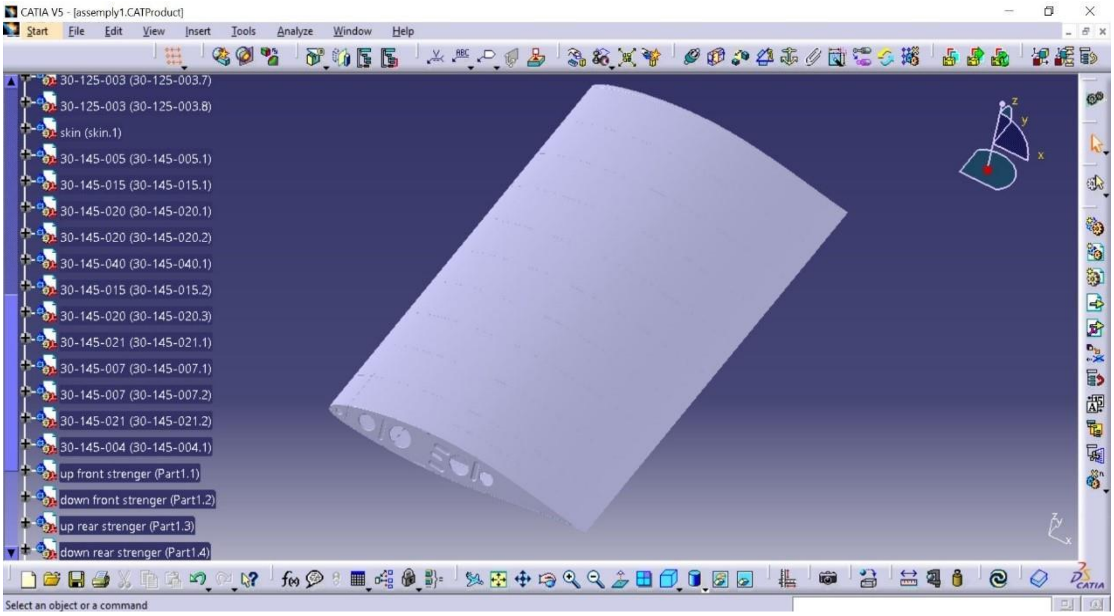


Figure 18: Wing draw with skin

Finally, the skin of entire wing structure was drawn by import the airfoil from dotdat file to CATIA through EXCEL, then extrude it by using pad option.

After that the edge of the extruded airfoil was projected to offset it by value of thickness of airfoil then extrude it.

Finally, subtract them from other

3.2 ANSYS Workbench

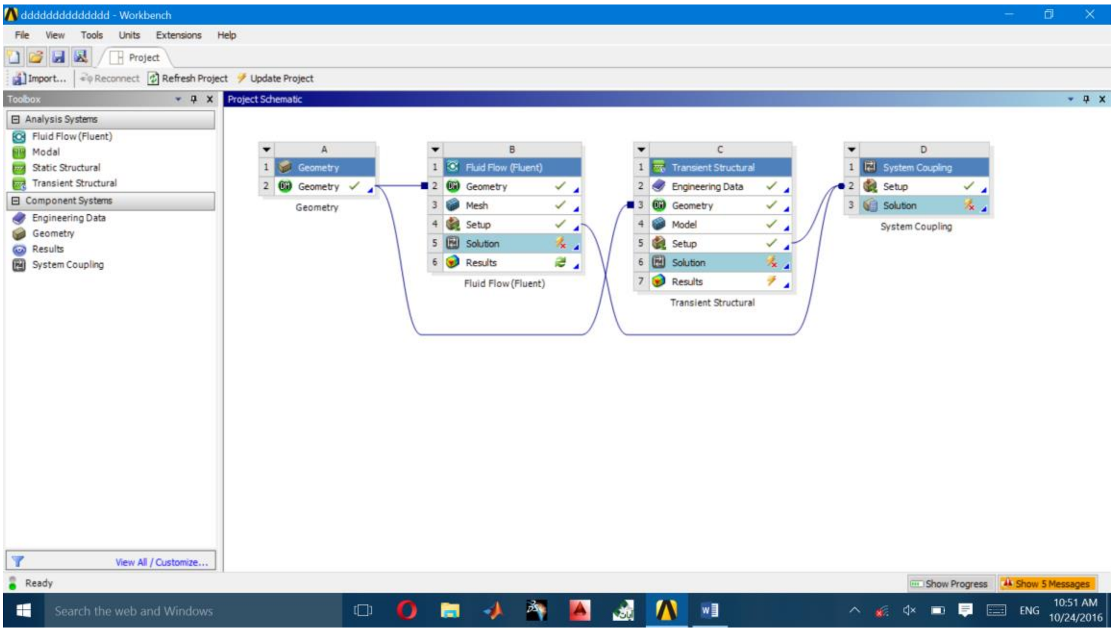


Figure 19: ANSYS Workbench

The geometry (domain and wing structure) was entered into geometry part then branch from geometry part to Fluid flow (fluent) part was connected and transient structural part and branch from setup of fluid Flow(fluent) to setup of system coupling in addition to branch from setup of transient structural to setup of system coupling.

The wing structure at fluid flow(fluent) part suppressed but at transient structural part the domain was suppressed.

3.3 CFD setup

The domain of wing was drawn and subtracted the wing from it as shown in figure 20, this domain is drawn to be suitable to FLUENT.

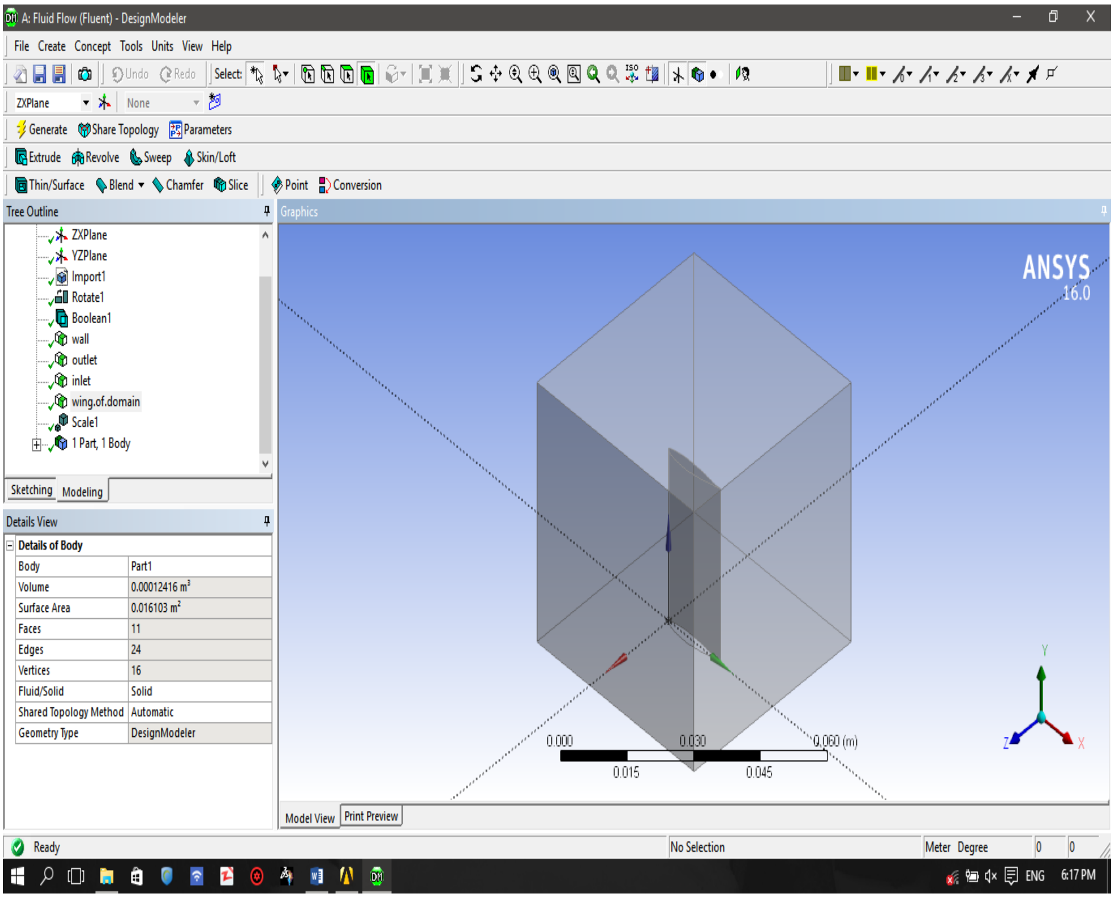


Figure 20: Wing draw with domain

Table 4: Domain Specifications

Surface Area	2.411e+009 mm²
Volume	7.9992e+012 mm³

Meshing to that domain was ruined by the following specifications

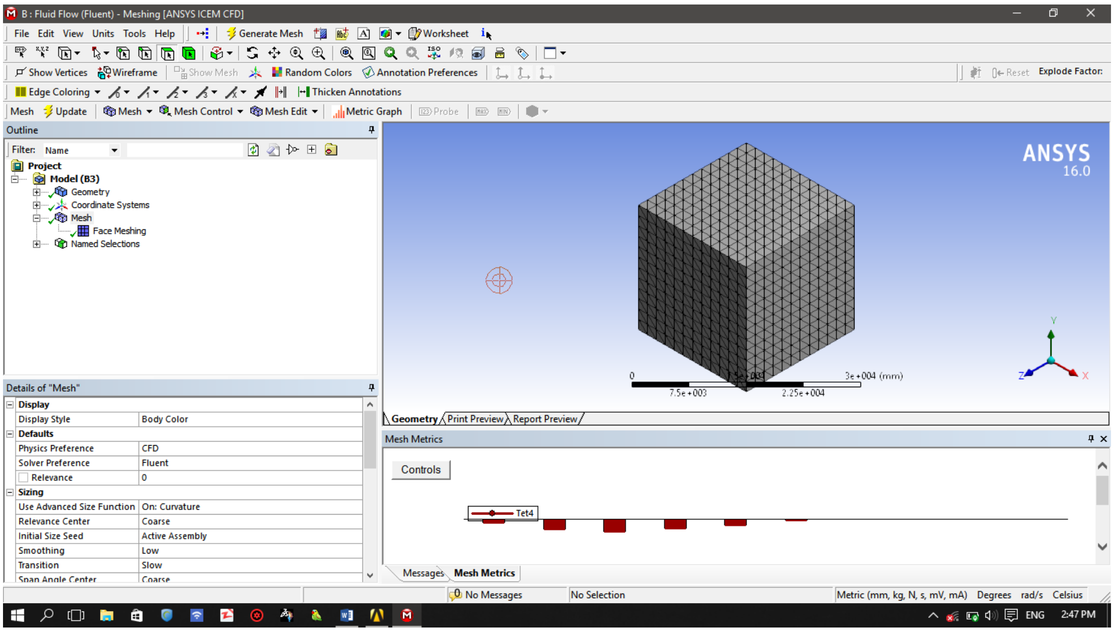


Figure 21: Meshing the domain

Table 5: Meshed Domain Specifications

Min size of Elements	17.22 mm
Max size of Elements	3453.3 mm
Growth rate	1.4
No. of Nodes	6486 nodes
No. of Elements	33268 elements
Average skewness	0.283

Then the setup of the fluent was adjusted as shown in figure 22

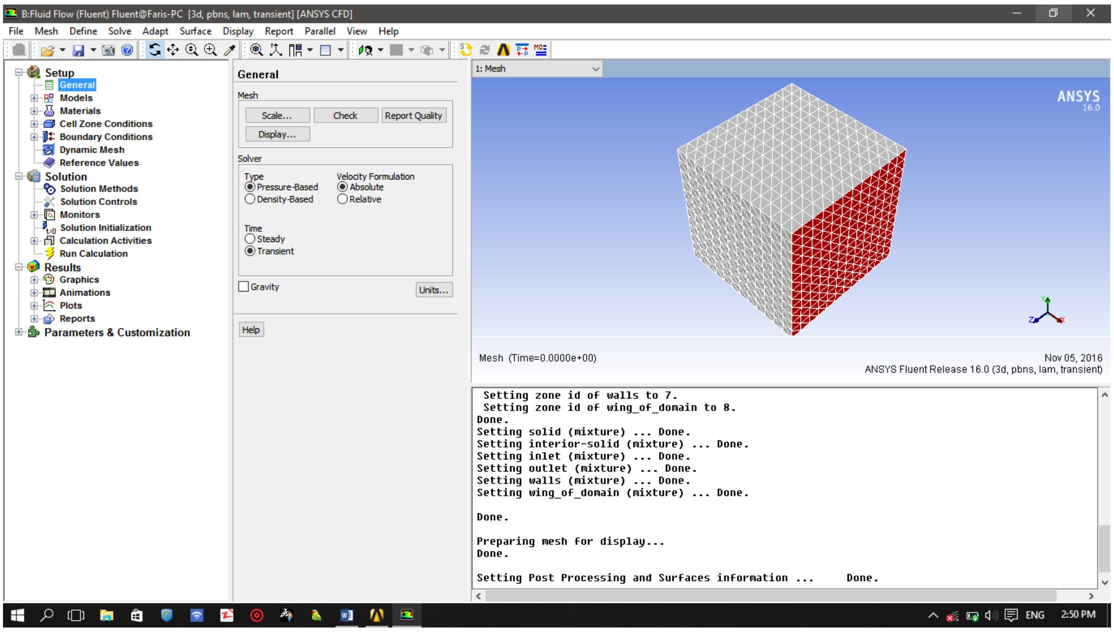


Figure 22: FLUENT Solution

The type of solver is pressure based and time is transient

Then the velocity of inlet selected, firstly substitute the velocity was substituted as

20% more than dive velocity (V_{div}). This (V_{dive}) is obtained from equation

$$V_{div} = 1.4 * V_{cruise} \ldots\ldots\ldots\ldots\ldots 6$$

Then the velocity was selected at inlet as

$$1.2 * V_{div} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

Then dynamic mesh was ruined with smoothing mesh method

After that smoothness selected method as diffusion

With diffusion parameter 2

Then create that dynamic mesh with wing as zone type system coupling

The type of scheme selected in pressure velocity coupling in solution method as simple

Then the calculation ruined by following parameters

Table 6: FLUENT inputs

Input Speed	1.2*V_{div}
No. of Time step	50 steps
Time Step Size	0.01s
V_{cruise}	51.4 m/s
V_{div}	71.94 m/s
Diffusion Parameter	2

Then the materials of wings were added as shown in table 8

Table 7: Materials used in wing

Spars, Strangers	Aluminum alloy 7075-T6
Skin, Ribs	Aluminum alloy 2024-T3

Then mesh ruined to wing (with suppression the domain)

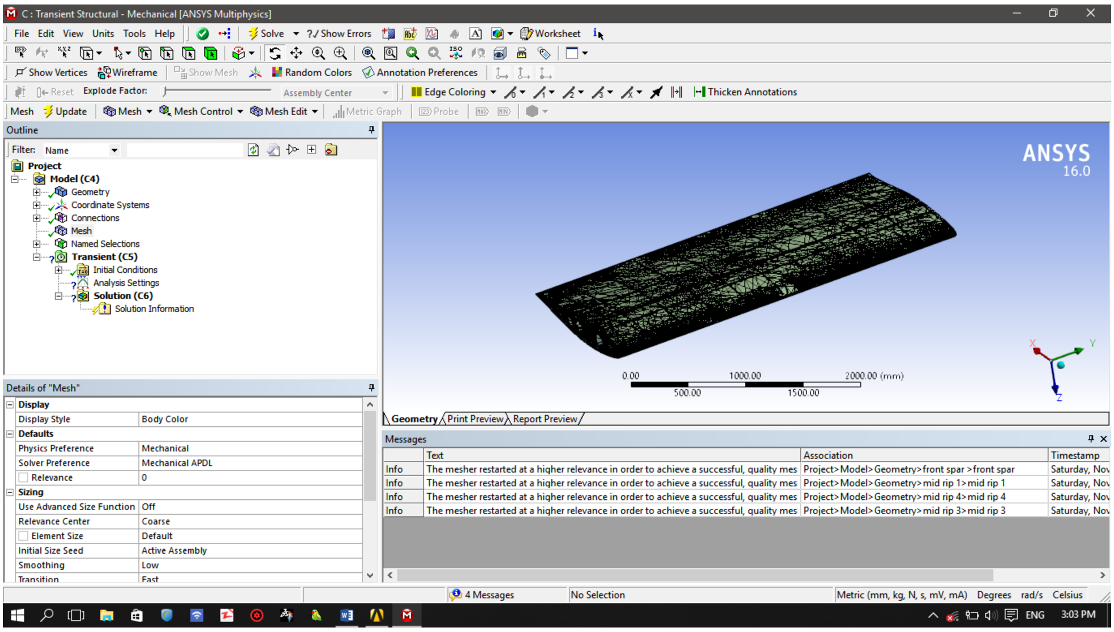


Figure 23: Meshing the wing

the smoothness was adjusted as medium, in addition to transition as fast

Table 8: Mesh Output

Min Edge Length	2.5842e-002 mm
No. of nodes	510797 nodes
No. of elements	252510 elements
Min Skewness	9.8228e-002

On the other hand, fluid solid interface set as skin and fixed support as the root.

Then two data transfer was created to satisfy the two-way concept

For first data transfer

At source fluid structure interaction selected as participant, wing of domain as region.

And force as variable, at target transient structure selected as participant, fluid solid interface as region and force as variable.

For second data transfer

Then opposite the participant and region in the second data transfer, increment displacement as variable and displacement as variable

Table 9: System Coupling Inputs

Time Step	0.01s
Iteration	5 iterations

Finally, running the solution

3.4 Analytical calculation

Flutter speed and divergence speed calculated.

Flutter speed is obtained from MATLAB code, but the divergence speed is obtained from equations.

3.4.1 Divergence speed

$$V_{divergence} = \sqrt{2 * \frac{GJ}{e\rho ca} * \left(\frac{\pi}{2L}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

Where

$$GJ = \frac{T}{\theta/L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

The value of GJ was obtained from ANSYS software by given value of torque, that give angle of twist with given value of length.

3.4.2 Flutter speed

This speed was obtained from the following MATLAB code in appendix A

In MATLAB code there is some parameters (kappa frequency and theta frequency) we calculated from following equations

$$w_h = \sqrt{\frac{v_h}{m}} \ldots\ldots\ldots\ldots\ldots\ldots 10$$

$$w_\theta = \sqrt{\frac{k_\theta}{I_p}} \ldots\ldots\ldots\ldots\ldots\ldots 11$$

Chapter four: Reslts and discussion

The flutter is obtained from MATLAB code that presented in APPENDEX A[4]

First, the kappa frequency was calculated from equation 10, Secondly the theta frequency was calculated from equation 11.

Finally, flutter can be obtained by substituting the all parameter.

Table 10: Values of frequencies and Flutter speed

Kappa Frequency	104.03 rad/s
Theta Frequency	488.24 rad/s
Flutter Speed	94.7 m/s

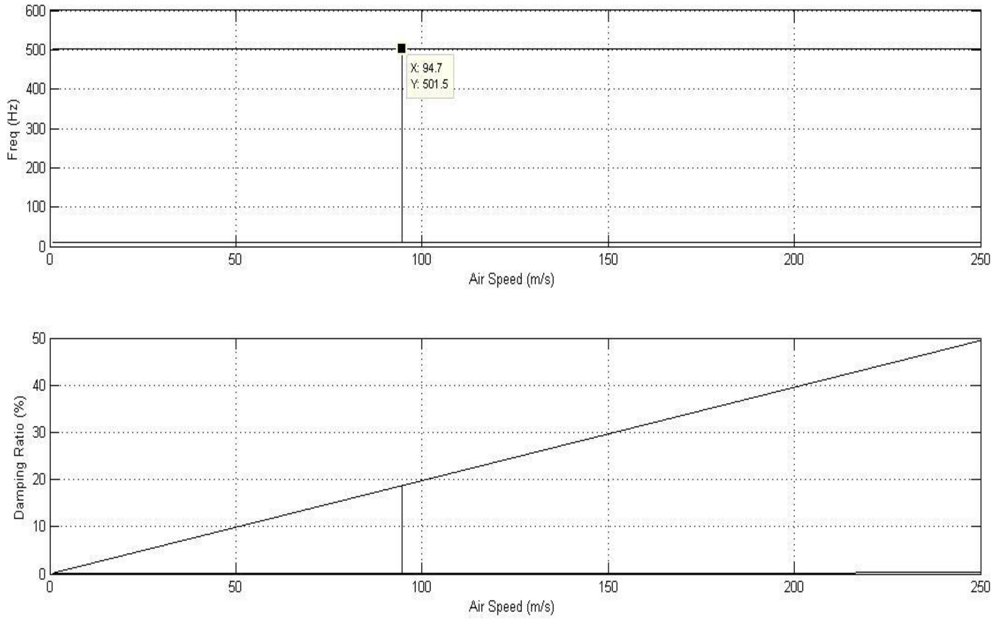


Figure 24: Flutter Curve (Frequency vs Airspeed)

This curve is representing the frequency vs airspeed; from the above curve the linearity variation of damping ratio with air speed.

The flutter speed is indicated corresponding to damping ratio equal to 18.89%

The current density corresponds to current altitude.

Then applying theoretical equations to calculate divergence speed

Table 11: divergence equation parameters and divergence speed

Torsion Stiffness	58877.876 $N.m^2$
(e) or (the space between elastic center and aerodynamic center)	0.243 m
Density	0.817 kg/m^3
Divergence speed	119.4 m/s

This results are very acceptable because the flutter speed always lesser than divergence speed generally.

Chapter five: Conclusion, Recommendation

5.1 Conclusion

This project dealt with the application of the concept of fluid structure interaction for the estimation of flutter speed utilizing ANSYS workbench. The problem had been setup in ANSYS environment, but due to the limitation of computation hardware (computer) the problem solution still a problem.

Another way to estimate the divergence and flutter speeds is to use Galerkin approach for energy, that used as a verification method and MATLAB code used to estimate the flutter frequency and speed. The obtained results showed that the flutter occurred at 94.7m/s. where the dive speed is m/s, which satisfy the regulations. Where the divergence speed calculated and found 119.4m/s.

Hence, the analytical calculations of flutter and divergence speeds has been satisfied, but the numerical solution and examine of wing deformation by ANSYS is not satisfied because it requires high performance requirements and the wing structure is very complicated also it consists a lot of details so availability of supercomputer is very important.

5.2 Recommendation

We strongly recommended to continue the work, this need to explore ANSYS more and to simplify the wing internal structural component.

Also to validate the obtained results utilizing NASTRAN PATRAN as a tool because it consists of special branch of aeroelasticity analysis.

5.3 Future work

Use experimental analysis in order to obtain flutter and divergence speeds to validate the results from the computational and analytical methods.

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Appendix A

```
% Flutter Chapter B04 Appendix

% Sets up the aeroelastic matrices for binary aeroelastic model,

% performs eigenvalue solution at desired speeds and determines the frequencies

% and damping ratios

% plots V_omega and V_g trends

% and plots flutter conic solution

% Initialize variables

clear; clf

% System parameters

s = 3.3266; % semi span

c = 1.618985; % chord

m = 39.04/(3.3266*1.618985); % unit mass / area of wing

kappa_freq =104.03; % flapping freq in Hz

theta_freq = 231.239; % pitch freq in Hz

xcm = 0.5*c; % position of centre of mass from nose

xf = 0.4*c; % position of flexural axis from nose

e = xf- 0.25*c; % eccentricity between flexural axis and aerocentre (1/4 chord)

velstart = 1; % lowest velocity

velend = 1000; % maximum velocity

velinc =0.1; % velocity increment

a = 6.85; % 2D lift curve slope

rho = .817; % air densit
```

```
Mthetadot = -1.2; % unsteady aero damping term

M = (m*c^2 - 2*m*c*xcm)/(2*xcm); % leading edge mass term

damping_Y_N = 1; % =1 if damping included =0 if not included

if damping_Y_N == 1

% structural proportional damping inclusion C = alpha * M + beta * K

% then two freqs and damps must be defined

% set dampings to zero for no structural damping

z1 = 0.0; % critical damping at first frequency

z2 = 0.0; % critical damping at second frequency

w1 = 2*2*pi; % first frequency

w2 = 14*2*pi; % second frequency

alpha = 2*w1*w2*(-z2*w1 + z1*w2)/ (w1*w1*w2*w2);

beta = 2*(z2*w2-z1*w1) / (w2*w2 - w1*w1);

end

% Set up system matrices

% Inertia matrix

a11=(m*s^3*c)/3 + M*s^3/3; % I kappa

a22= m*s*(c^3/3 - c*c*xf + xf*xf*c) + M*(xf^2*s); % I theta

a12 = m*s*s/2*(c*c/2 - c*xf) - M*xf*s^2/2; %I kappa theta

a21 = a12;

A=[a11,a12;a21,a22];

% Structural stiffness matrix

k1 = (kappa_freq*pi*2)^2*a11; % k kappa heave stiffness
```

```
k2 = (theta_freq*pi*2)^2*a22; % k theta pitch stiffness

E = [k1 0; 0 k2];

icount = 0;

for V = velstart:velinc:velend % loop for different velocities

icount = icount +1;

if damping_Y_N == 0; % damping matrices

C = [0,0; 0,0]; % =0 if damping not included

else % =1 if damping included

C = rho*V*[c*s^3*a/6,0;-c^2*s^2*e*a/4,-c^3*s*Mthetadot/8] +alpha*A + beta*E;

% Aero and structural damping

end

K = (rho*V^2*[0,c*s^2*a/4; 0,-c^2*s*e*a/2])+[k1,0; 0,k2]; % aero / structural stiffness

Mat = [[0,0; 0,0],eye(2); -A\K,-A\C]; % set up 1st order eigenvalue solution matrix

lambda = eig(Mat); % eigenvalue solution

% Natural frequencies and damping ratios

for jj = 1:4

im(jj) = imag(lambda(jj));

re(jj) = real(lambda(jj));

freq(jj,icount) = sqrt(re(jj)^2+im(jj)^2);

damp(jj,icount) = -100*re(jj)/freq(jj,icount);

freq(jj,icount) = freq(jj,icount)/(2*pi); % convert frequency to hertz

end
```

```
Vel(icount) = V;

end

% Plot frequencies and dampings vs speed

figure(1)

subplot(2,1,1); plot(Vel,freq,'k');

vaxis = axis; xlim = ([0 vaxis(2)]);

xlabel ('Air Speed (m/s) '); ylabel ('Freq (Hz)'); grid

subplot(2,1,2);

plot(Vel,damp,'k')

xlim = ([0 vaxis(2)]); axis([xlim ylim]);

xlabel ('Air Speed (m/s) '); ylabel ('Damping Ratio (%)'); grid
```