Sudan University of Science and Technology
College of Graduate Studies
Department of Mechanical Engineering

VALIDATION OF REDESIGNED ZAGIL AIRCRAFT WING

التحقق من إعاده تصميم جناح الطائره زاجل

Partial fulfillment of the Requirements for the degree of Master of Science in Mechanical Engineering (Power)

By

Mohamed Omer Mohamed Ahmed

Sudan University of Science and Technology

Supervisor

Dr. Sakhr Babikir Hassan Abu Darag

Oct 2019

بسم الله الرحمن الرحيم

يقول تعالى:

((وَأَعِدُّوا لَهُمْ مَا اسْتَطَعْتُمْ مِنْ قُوَّةٍ وَمِنْ رِبَاطِ الْخَيْلِ تُرْهِبُونَ بِهِ عَدُوَّ اللَّهِ وَعَدُوَّكُمْ وَآخَرِينَ مِنْ دُونِهِمْ لَا تَعْلَمُونَهُمُ اللَّهُ يَعْلَمُهُمْ وَمَا تُنْفِقُوا مِنْ شَيْءٍ فِي سَبِيلِ اللَّهِ يُوَفَّ إِلَيْكُمْ وَأَنْتُمْ لَا تُظْلَمُونَ))

صدق الله العظيم

الأنفال 60

Dedication

Dedicated to:

My family

The spirit of my lovely aunt bothaina

My friends

Acknowledgment:

Thanks and appreciation to the supervisor Dr. Sakhr Abu Darag for his assistance, guidance, encouragement and cooperation during the research period.

Thank goes also to the teaching staff of the Sudan University of Science and Technology, especially to the members of the Mechanical Engineering School.

Indeed, special thank extend to the Marbel Engineering Company for the great assistance in providing the test equipment needed and consultancy.

Abstract

The research studies the original design of (ZAGIL) wing from aeroelasticity point of view by enhancing computational software, theoretical approach and experimental tests to define the structural problem that existed in the wing.

The presence of a high stress zone in wing skin, ribs, spar and trialing edge occurs at operating condition Mach number 0.6 and angle of attack 12 degree considered as a main structural problem in the original wing of (ZAGIL) aircraft.

ANSYS fluent software and experimental tests results have been used to validate the aerodynamic and structural results obtained by finite element modeling and post processing (FEMAP) software, and the graphs show good agreement for both, aerodynamic and structural results.

To satisfy the working operation condition for the redesigned wing, the redesigned wing skin is compacted with leading edge, trailing edge and spar by using extrusion technology to manufacture the wing without rips.

المستخلص

هذا البحث يدرس التصميم الأصلي لجناح الطائره زاجل من وجهة نظر المرونه الهوائيه بمساعده البرامج التحسيبيه والطرق النظريه والتجارب العمليه لمعرفه المشاكل الإنشائيه التي تحدث في الجناح

يعتبر ظهور اجهادات عاليه في جلد و ضلوع و حافه الجناح عند تشغيل الجناح برقم ماخ 0.6 وزاويه هجوم 12 درجه هو المشكله الإنشائيه الأهم

نتائج برنامج الأنسيس فلونت و النتائج العمليه استخدمت لتأكيد النتائج الإيروديناميكيه والإنشائيه التي تم الحصول عليها من برنامج الفيماب والمخططات اظهرت تقارب النتائج الإيروداينميكيه والإنشائيه

لتلبيه متطلبات ظروف التشغيل للجناح المعدل تم دمج الجلد والحافتين الأماميه والخلفيه والأضلع والساريه بإستخدام تكنولوجيا البثق لتصنيع الجناح بدون أضلع

Table of contents

List of symbols:

Symbol	Description	Unit
V_D	Divergence speed	m/s
S	Wing area	m^2
b	Wing span	m
M_0	Pitching moment	Nm
AOA	Angle of attack	rad
Ma	Mach number	Dimensionless
AR	Aspect ratio	Dimensionless
C_l	Lift coefficient	Dimensionless
L	Lift force	N
$\mathrm{C}_{\theta\theta}$	Torsional stiffness	Nm/rad
ec	Distance between aerodynamic center and elastic center	m
$\propto$	Initial wing incidence	rad
c	Chord length	m
$\mathrm{C}_{\mathrm{L}\propto}$	Wing lift curve slope	/rad
M_t	Moment of torsion	N.m
J	Torsional constant	m^4
G	Modulus of rigidity	N/m^2

List of abbreviations:

Abbreviations	Description
FEMAP	Finite Element Modeling And Post Processing
CFD	Computational Fluid Dynamics
ANSYS	Analysis System
FLUENT	Commercial Computational Software

Greek symbols:

Symbol	Description	unit
α	Angle of Attack	deg
ρ	Density	Kg/m^3
θ	Elastic twist of the wing	deg

Chapter one

Introduction

1.1 General Introduction:

A flight vehicle is a complex structural system with numerous variables and constraints. The number of design variables and alternate constructions is large to be fixed by the governing equations and constraints. Airframe designers usually resort to past experience and similar existing designs to fix the values of undetermined [1].

In aerospace applications, wing design is a crucial and important part which is considered as a key attribute of aircraft aeroelastic design. Therefore, it is important to develop a high efficiency aeroelastic optimization method for wing structure design [2].

The increased wing span of these vehicles stems from a desire to decrease the induced drag of the wing (and thus improve key metrics like specific fuel consumption) but can result in a highly flexible wing, potentially susceptible to onerous issues (static and dynamic) associated with the flight loading [3].

(ZAGIL) is a light aircraft fly with $M < 0.6$ and with maximum working altitude 8 km. It has two wings with span of 2.382 m contain skin, leading edge, spar, ribs and trialing edge. All wing parts are made from aluminum 60-61 T6.

FEMAP (Finite Element Modeling And Post-processing) is an engineering analysis program that used to build finite element models of complex engineering problems (pre-processing) and view solution results (post-processing) it runs on Microsoft windows and provides CAD import, modeling and meshing tools to create a finite element model as well as post-processing and is typically used in the design process to reduce costly prototyping and testing and for structural optimization to reduce weight.

CFD (Computational Fluid Dynamic) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows.

1.2 Scope of the Research:

Since the design of the (ZAGIL) aircraft wing does not follow the elastic collapse theories at Mach = 0.6 which is the target, therefore a redesign for the wing parameters is required.

The research will concentrate on study the existed wing in stage of design and analysis. The mechanical and aerodynamic properties will be tested by FEMAP, CFD soft wares and laboratory testing equipment’s.

1.3 Problems:

1. The aeroelastic analysis of (ZAGIL) A/C wing show high stress zone in spar and skin exceed the material’s yield stress at (Mach=0.6).
2. The static analysis of (ZAGIL) A/C wing show high stress zone in spar and skin exceed the material’s yield stress at general A/C load factor.

1.4 Objectives:

This project aims to:

1-Study the static and aeroelastic analysis of the (ZAGIL) wing in order to establish strong database documents.

2-Improve the existing wing design regarding of Aerodynamics and Aeroelasticity point of views.

3. Determine the working constraints of recent and improved wing for working flight condition Mach number, altitude and angle of attack.

1.5 Methodology:

- Library research.
- Practical exercise in workshop (Experimental work) used to calculate the torsional stiffness of wings by applying torsion moment on wings and writing the deflection angle.
- Numerical methodology using FEMAP program to calculate the stresses at wing parts with different work conditions.

Chapter two

Literature Review

2.1 Literature Review

Wing is the main component to produce lift force in aircraft so aeroelastic design optimization is necessary in order to minimize the weight while keeping the stresses at all part of wing under the yield strength limit using analytical, computational and experimental data.

The aeroelastic design optimization is considered as an essential solution to sophisticated problem of airplane stability. Liviu Librescu and Karam Y. Maalawi [4]. They provided a novel mathematical approach to the aeroelastic optimization of a wing-type structure with objective function that maximize the divergence speed by linear and stepped thickness distribution along the entire length of the wing without violating the performance requirements imposed on the total structural weight.

Dillinger J.K.S, *et al* [5] are represented an optimized mass of three forward swept wings for balanced and unbalanced laminates. The optimizer was shown the unbalanced laminates better than the balanced laminates for all aeroelastic constraints considered.

Wan Zhiqiang, *et al* [2] have investigated an aeroelastic two-level optimization procedure suitable for the preliminary wing design. The first-level procedure is an aeroelastic optimization of structural layout which considers variations of structural layout and size parameters, while the second-level procedure is a robust aeroelastic optimization considering uncertainties in aerodynamic loads, structural layout parameters, and structural size parameters. The optimization method can provide an optimal structural layout and structural sizes for a wing in the preliminary design stage.

Scott Townsend, *et al* [6] showed that, applying flutter and divergence constraints on the eigenvalues of the flutter equation results in a robust design strategy capable of significantly reducing weight while maintaining or increasing flutter and/or divergence speed.

Yi Li and Tianhong Wang [7] combined the Taylor Expansion (TE) with the Optimization and Anti-optimization Problems (OAP) solutions of Parameterized Interval Analysis (PIA) to study the effect of structural uncertainties on the divergence of wing through two-dimensional wing example. The method developed by them is compared with the Classic Interval Analysis (CIA) and the result is indicated that, the noval technique can reduce over estimation in the classic interval analysis and the TE method. This beside, the interval of divergence dynamic pressure predicted by the develped method is as narrow as the one from the parameterized interval analysis combined.

YANG Chao, et al [10] have presented a method for structural design of flexible air vehicle considering the uncertainties in maneuver loads the critical design load cases were determined in four typical maneuvers and three objectives of critical loads were defined, focusing on the load status of three concerned sections on this basis, the aeroelastic optimization designs of a flexible wing were conducted in the cases of theoretical linear aerodynamic forces, experimental aerodynamic forces and predicted loads, respectively. The resulting optimal designs based on the predicted loads were heavier and more robust than the designs based on theoretical or experimental aerodynamic forces, which was attributed to the consideration of uncertainties in aerodynamic forces in the early phase of aircraft design.

Inaddition to these previous studies, Changchuan Xie, et al [9] are established a theoretical framework of aeroelastic optimization design for high-aspect-ratio wing considering structural nonlinear effects.
The results of nonlinear reanalysis show that the optimum solutions of linear case might be inaccurate when the wing produces large deformation, and it is necessary to consider the geometric nonlinearity in optimization design.

Chapter three

Analytical Approach

3.1 Introduction

In order to determine the working constraints of recent and improved wing, the theoretical approach gives a roughly estimation for the speed at which the wing will collapse (divergence speed).

3.2 Divergence speed V_D

The most common divergence problem is the torsional divergence of a wing. It is useful, initially to consider the case of a wing of area S without ailerons and in a two-dimensional flow, as shown in the following Figure 3.1.

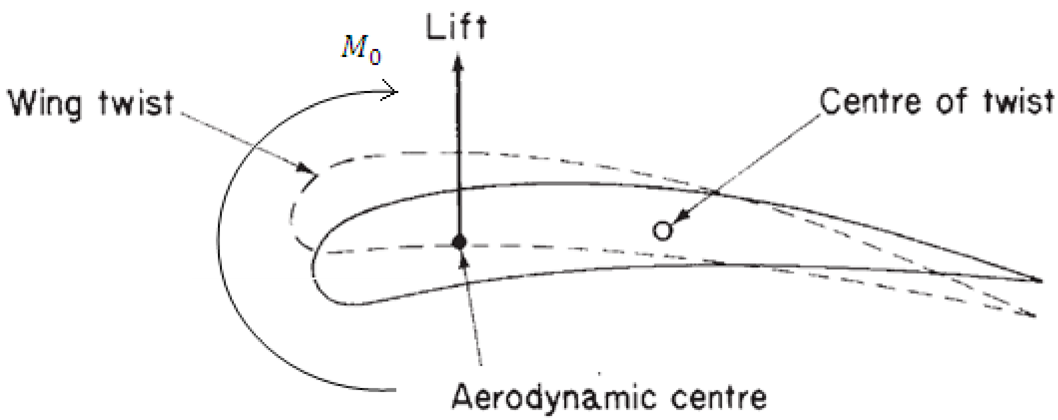


Figure 3.1: Increase of wing incidence due to wing twist.

The torsional stiffness of the wing represented by a spring of stiffness, $C_{\theta\theta}$, resists the moment of the lift vector, L, and the wing pitching moment, M_0, acting at the aerodynamic center of the wing Section. For moment equilibrium of the wing section about the aerodynamic center [8],

$$M_0 + L.ec = C_{\theta\theta}\theta \qquad \text{----------------------------- (3.1)}$$

Where, ec, is the distance of the aerodynamic center forward of the flexural center expressed in terms of the wing chord, c, and θ is the elastic twist of the wing.

From aerodynamic theory

$$M_0 = \frac{1}{2}\rho\, V^2 Sc\, C_{M,0} \qquad \text{-------------------------------------(3.2)}$$

$$L = \frac{1}{2}\rho\, V^2 S\, C_L \qquad \text{-------------------------------------- (3.3)}$$

Substituting in Equation (3.1) yields

$$\frac{1}{2}\rho\, V^2 S(c\, C_{M,0} + ec.C_L) = C_{\theta\theta}\theta \qquad \text{-------------------------- (3.4)}$$

Or, since

$$C_L = C_{L0} + \frac{\partial C_L}{\partial \propto}(\propto + \theta) \qquad \text{---------------------------------- (3.5)}$$

Where, $\propto$, is the initial wing incidence or, in other words, the incidence corresponding to a given flight condition.

Assuming that the wing is rigid and C_{L0} is the wing lift coefficient at zero incidence, then

$$\frac{1}{2}\rho V^2 S\left[c\,C_{M,0} + ecC_{L0} + ec\frac{\partial C_L}{\partial \propto}(\propto + \theta)\right] = \mathrm{C}_{\theta\theta}\theta \quad ---------- (3.6)$$

Where $\frac{\partial C_L}{\partial \propto}$ is the wing lift curve slope

Rearranging of the equation (3.6) gives

$$\theta = \frac{\frac{1}{2}\rho V^2 Sc\left[C_{M,0} + eC_{L0} + e\frac{\partial C_L}{\partial \propto}\propto\right]}{\mathrm{C}_{\theta\theta} - \frac{1}{2}\rho V^2 Sec\frac{\partial C_L}{\partial \propto}} \quad -------------------- (3.7)$$

Equation (3.7) shows that divergence occurs (i.e. θ becomes infinite) when

$$\mathrm{C}_{\theta\theta} = \frac{1}{2}\rho V^2 Sec\frac{\partial C_L}{\partial \propto} \quad --------------------------- (3.8)$$

The divergence speed V_d is then

$$V_d = \sqrt{\frac{2\mathrm{C}_{\theta\theta}}{\rho Sec\frac{\partial C_L}{\partial \propto}}} \quad --------------------------------- (3.9)$$

3.3 Section model

It called section model because it take the characteristic of section at (0.7— 0.75) b/2 and represent the entire wing as shown in figure 3.2.

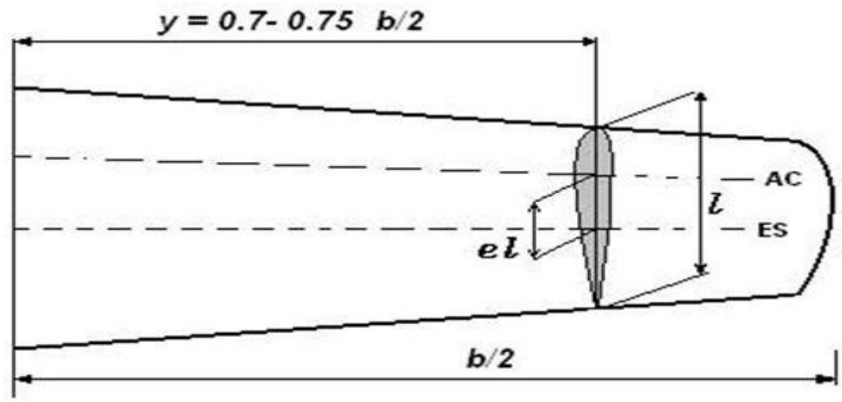


Figure 3.2: Section model.

When the aircraft speed increase the lift increase lead to increasing in stress which deform the airfoil as shown in the Figure 3.3.

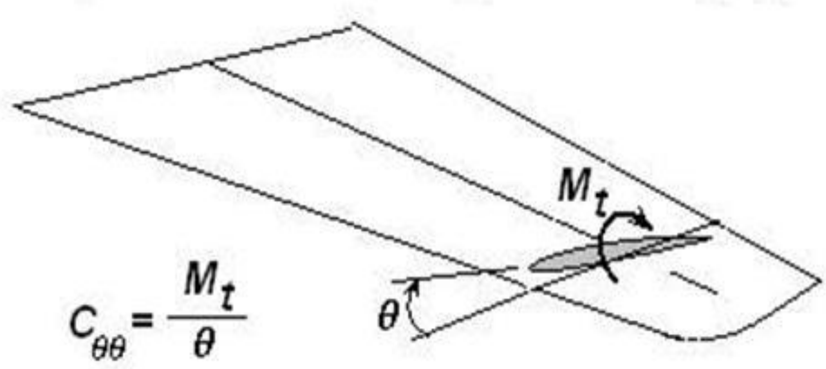


Figure 3.3: Moment of torsion effect on airfoil

$C_{\theta\theta}$ is the torsional rigidity and M_t is the moment of torsion

$$\frac{d\theta}{dL} = \frac{M_t}{GJ} \qquad \text{------------------------------------- (3.10)}$$

Where, *J*, is the torsional constant and *G* is the modulus of rigidity

$$d\theta = \frac{M_t}{GJ}\, dL \qquad \text{--------------------------------- (3.11)}$$

$$\theta = \int \frac{M_t}{GJ}\, dL = \frac{M_t}{GJ} \int dL \qquad \text{-------------------------------- (3.12)}$$

$$\theta = \frac{M_t}{GJ} L \qquad \text{------------------------------------ (3.13)}$$

Since,

$$C_{\theta\theta} = \frac{M_t}{\theta} \qquad \text{--------------------------------------- (3.14)}$$

$$\therefore \quad C_{\theta\theta} = \frac{GJ}{L} \qquad \text{-------------------------------------- (3.15)}$$

3.4 Analytical Calculation for original wing

Table 3.1 data of (ZAGIL) wing

parameter	symbol	value
Wing chord	c	$0.1915\ m$
Wing span	$\frac{b}{2}$	$1.048\ m$
density	ρ	$1.225\frac{Kg}{m^3}$
Modules of rigidity	G	$26\ GPa$

Analytical solution is used to determine the divergence speed of (ZAGIL) wing. Equation (3.9) reads

$$V_d = \sqrt{\frac{2C_{\theta\theta}}{\rho Sec\frac{\partial C_L}{\partial \alpha}}}$$

Air density at sea level

$$\rho = 1.225\frac{Kg}{m^3}$$

Wing area (S)

$$S = c.\frac{b}{2} = 0.1915 \times 1.048 = 0.200692\ m^2$$

Lift gradient $\left(\frac{\partial C_L}{\partial \alpha}\right)$

$$\frac{\partial C_L}{\partial \alpha} = \frac{\alpha_0}{1 + \left(\frac{\alpha_0 \times 57.3}{\pi AR}\right)(1 + \tau)}$$

Aspect ratio (*AR*)

$$= \frac{b}{2c} = \frac{1.048}{0.1915} = 5.472$$

$$\alpha_0 = 0.1$$

$$\tau = 0.25$$

$$\therefore \ \frac{\partial C_L}{\partial \alpha} = 4.044/rad$$

Torsional stiffness, $C_{\theta\theta}$,

$$C_{\theta\theta} = \frac{G\ J}{L}$$

Modules of rigidity (*G*)

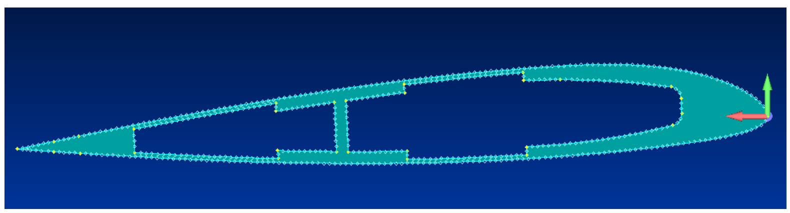
$$G = 26\ GPa$$

$$L = 0.7.\frac{b}{2} = 0.7 \times 1.048 = 0.7336\ m$$

Torsional constant (J) and Distance between aerodynamic and elastic centers (ec) for the cross section represented by following figure using FEMAP software

$$J = 1.51.10^{-7} m^4$$

$$ec = 0.002621\, m$$



$$C_{\theta\theta} = \frac{26.10^9 \times 1.51.10^{-7}}{0.7336} = 5351\, Nm/rad$$

$$V_d = \sqrt{\frac{2 \times 5351}{1.225 \times 0.200692 \times 0.002621 \times 4.044}}$$

$$V_d = 2026.5\, m/s$$

That equal to 5.96 Mach

3.5 Analytical calculation for redesigned wing

Analytical solution is used to determine the divergence speed of (ZAGIL) redesigned wing. Equation (3.9) reads

$$V_d = \sqrt{\frac{2C_{\theta\theta}}{\rho Sec\frac{\partial C_L}{\partial \alpha}}}$$

Air density at sea level

$$\rho = 1.225\frac{Kg}{m^3}$$

Wing area (S)

$$S \;= c.\frac{b}{2} = 0.1915 \times 1.048 = 0.200692\, m^2$$

Lift gradient $\left(\frac{\partial C_L}{\partial \alpha}\right)$

$$\frac{\partial C_L}{\partial \alpha} = \frac{\alpha_0}{1 + \left(\frac{\alpha_0 \times 57.3}{\pi AR}\right)(1+\tau)}$$

Aspect ratio (*AR*)

$$= \frac{b}{2c} = \frac{1.048}{0.1915} = 5.472$$

$$\alpha_0 = 0.1$$

$$\tau = 0.25$$

$$\therefore \;\; \frac{\partial C_L}{\partial \alpha} = 4.044/rad$$

Torsional stiffness, $C_{\theta\theta}$,

$$C_{\theta\theta} = \frac{G\,J}{L}$$

Modules of rigidity (G) $G = 26\,GPa$ $L = 0.7.\frac{b}{2} = 0.7 \times 1.048 = 0.7336\,m$

Torsional constant (J) and Distance between aerodynamic and elastic centers (ec)

for the cross section represented by following figure using FEMAP software

$$J = 2.3 * 10^{-7} m^4$$

$$ec = 0.020499\,m$$

$$C_{\theta\theta} = \frac{26.10^9 \times 2.3 * 10^{-7}}{0.7336} = 8162\,Nm/rad$$

$$V_d = \sqrt{\frac{2 \times 8162}{1.225 \times 0.200692 \times 0.020499 \times 4.044}}$$

$V_d = 894.9\,m/s$ That equal to 2.63 Mach

Chapter four

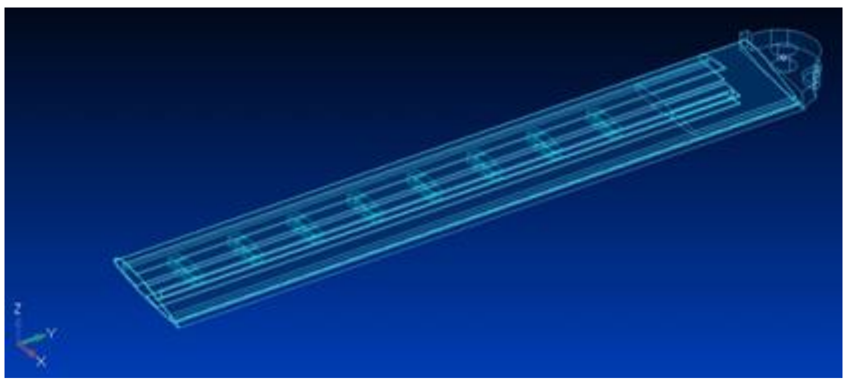
Computational Approach

4.1 Introduction

The original and redesigned wings design will be tested using FEMAP software and the aerodynamic load applied in FEMAP will be verified by the lift force generated from ANSYS FLUENT software.

4.2 Importing the geometry

The wing geometry imported to FEMAP by its original dimension in 3D whiles the chord in the X direction and the span in the Y direction. Every part is located in separated layer in order to be meshed.



4.3 Material defining

The material used to mesh the geometry is AL 6061-T6 and it is mechanical property defined as young modules and Poisson ratio whereas the density is defined as a physical property represented in table 4.1

Table 4.1 Material Property

Property	
Young modules [GPa]	68.9
Poisson ratio	0.33
Density [Kg/m^3]	2700

4.4 Mesh Creation

The mesh used in the analysis is two types:

1- Plate mesh

The plate mesh is used to mesh the skin because the plate mesh is used for small thickness such as the skin. The plate mesh type is quad because the skin shape is like rectangular.

2- Solid mesh

The solid mesh is used to mesh all parts of wing because they have big thickness. The solid mesh type is tri type, because this part has complicated shape.

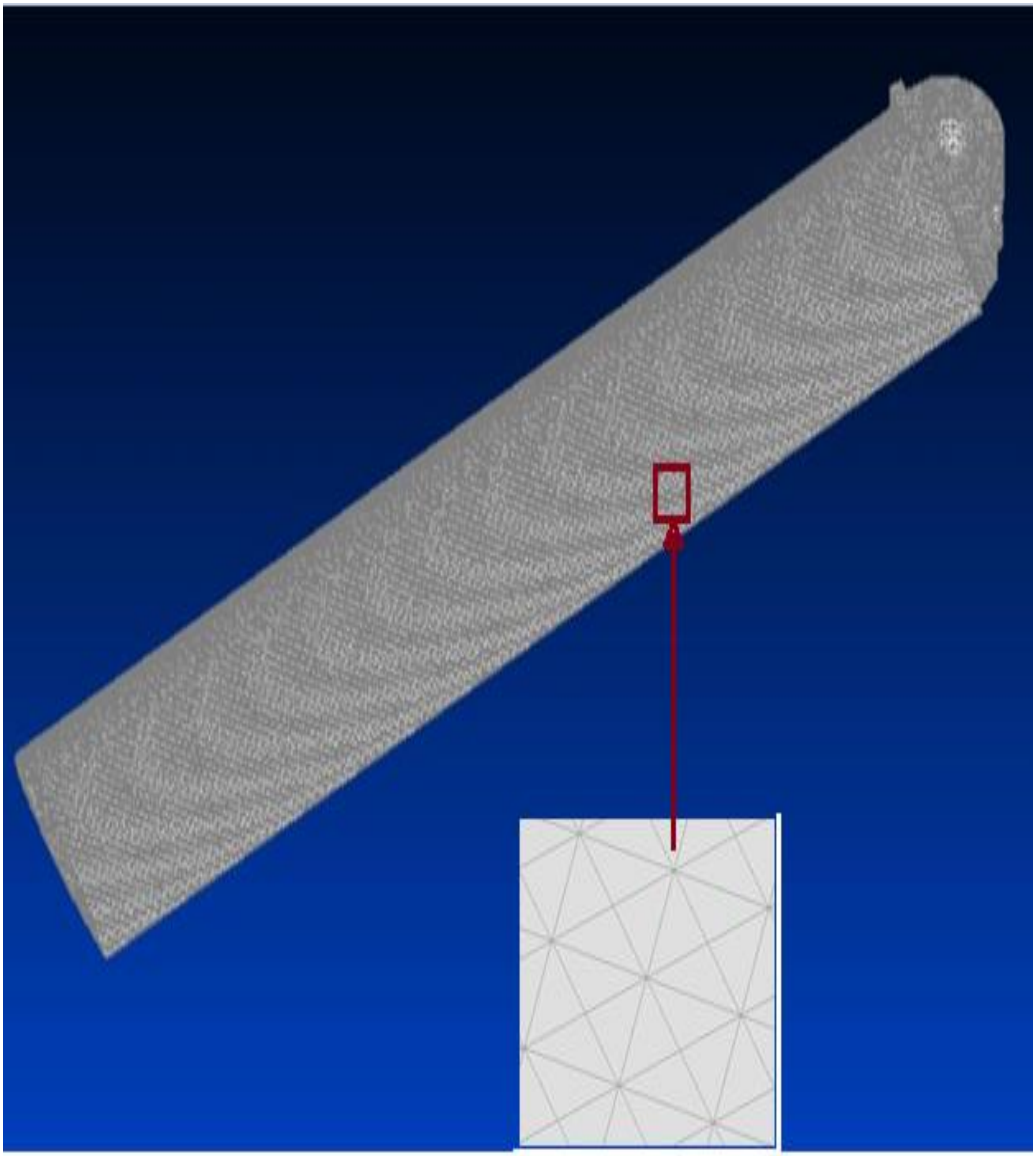


Figure4.3: Meshing the (ZAGIL) wing

4.5 Definition of Boundary Condition:

4.5.1 Constrain

Figure4.4: The constrain set

The hole of root attachment fixed for translation in X Y Z and for rotation in X Y Z

4.5.2 Aerodynamic Load

The load used in divergence analysis is aerodynamic load and it is produced by aerodynamic panel and transported to the structural model by connecter called spline.

4.5.2.1 Aerodynamic Panel

Aerodynamic panel create the aerodynamic load that produced in the wing by the dynamic pressure and angle of attack the length of the aerodynamic panel is the span and the width is the chord as the aerodynamic panel is fine the aerodynamic load result is accurate as shown in (figure4.5) 500 panel used to produce the aerodynamic load 50panel along the span and 10panel along the chord

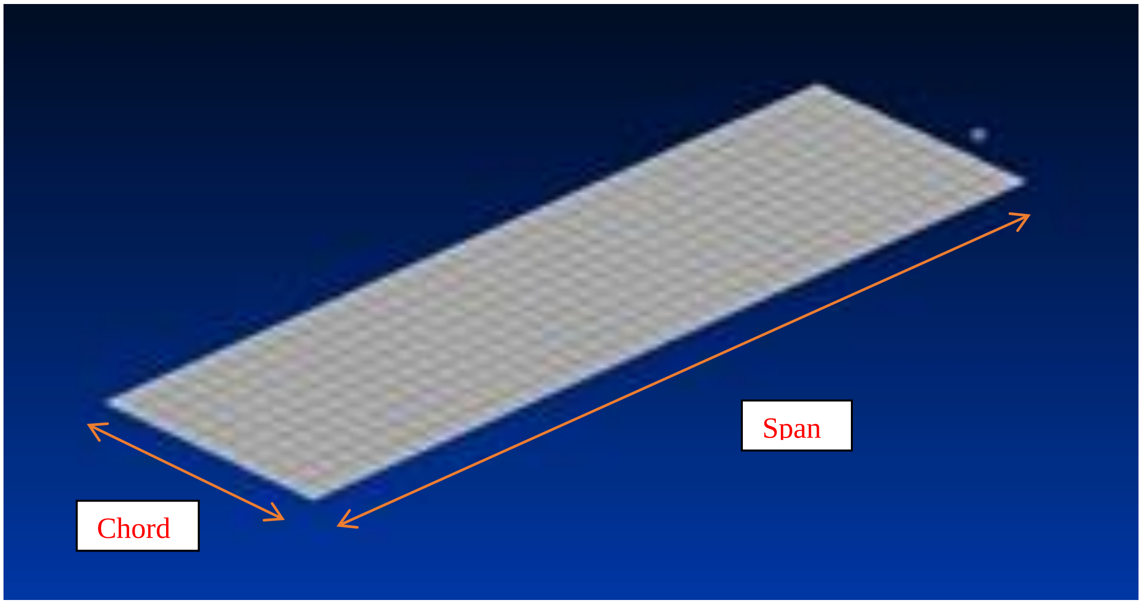


Figure4.5: Aerodynamic Panel

4.5.2.2 Aerodynamic Spline

Aerodynamic spline used to connect the aerodynamic model to the structural model and transport both load and translation between them.

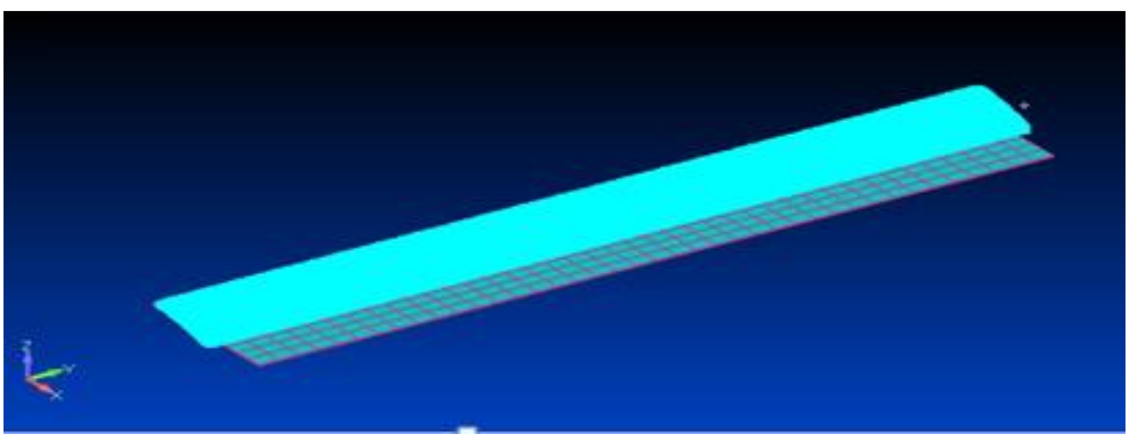


Figure4.6: Aerodynamic Spline

4.6 Computational Results

4.6.1 Maximum vonmises stress for the original wing

The maximum vonmises stress at Skin and Root of original wing for Mach number 0.2, 0.4, 0.5, 0.6 and 0.8 and for angle of attack α = 9 degree is illustrated in table 4.2

Table 4.2: Aeroelastic result for original wing

Part / Mach No	Skin [Mpa]	Root [Mpa]
M=0.2	33.82122	58.72879
M=0.4	101.6255	176.4674
M=0.6	228.6574	397.0516
M=0.7	311.2281	540.4313
M=0.8	406.502	705.8694

4.6.2 Maximum vonmises stress for the redesigned wing

The maximum vonmises stress of redesigned wing is represented in table 4.3

Table 4.3: Aeroelastic result for redesigned wing at the same condition

Part / Mach No	Skin [Mpa]	Root [Mpa]
M=0.2	42.21131	35.53679
M=0.4	168.8452	142.1472
M=0.6	379.9018	319.8311
M=0.7	517.0885	435.3257
M=0.8	675.381	568.5887

4.6.3 Lift force computed by FEMAP

FEMAP software use panel method to estimate the lift force acting on the wing structure. Indeed, as the number of panel increase the precision of the lift force calculated is increase. For this wing 500 panels are used (10 in the chord and 50 along the span)The Lift Force is calculated at different Mach number 0.2, 0.4, 0.6, 0.8 and 0.95 versus angle of attack (AOA) =10.5 degree.

Tables 4.4: Lift force calculated by FEMAP

Mach number	Lift force [N]
0.2	426
0.4	1700
0.6	3840
0.8	6820
0.95	9490

4.6.3 Lift force computed by ANSYS FLUENT

The lift force is calculated using ANSYS FLUENT in order to validate the lift results obtained by FEMAP at the same operation condition

Tables 4.5: Lift force calculated by ANSYS FLUENT

Mach number	Lift force [N]
0.2	327.6
0.4	1346.9
0.6	3291.6
0.8	6204.9
0.95	7780.9

Chapter five

Experimental method

5.1 Introduction

An Aeroelastic phenomenon such as divergence speed is expensive and dangerous to test so ground tests used in state of actual test.

Ground test and flight test methods are described that may be used to highlight potential structural problems that occur on aircraft. Primary interest is focused on light-weight general aviation airplanes. The structural problems described here is torsional stiffness.

5.2 Torsional stiffness measuring device

The torsional stiffness of the wing is defined by applying a different torques on the wing by using loading fixture for applying moments [11] as shown in Figure 5.1and measure the torsion angle happened in the wing by using a measurement way as indicated in Figure 5.2 and according to equation (5.1).

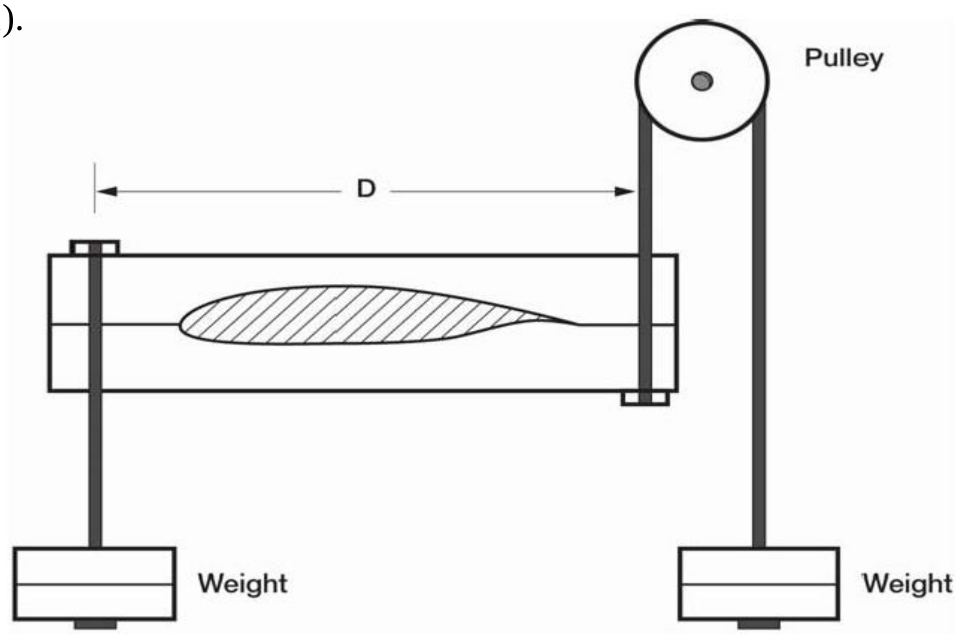


Figure 5.1: Loading fixture for applying moments

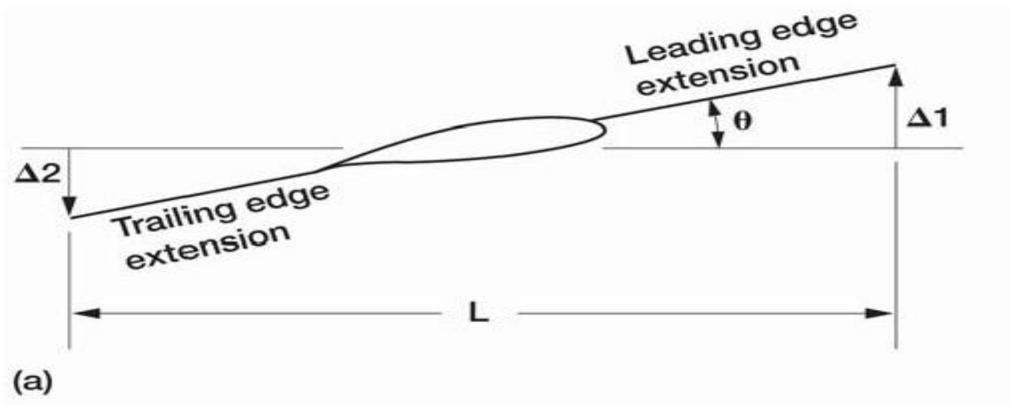


Figure 5.2: Torsion angle calculation

The torque will be applied on 0.7b of wing span and the angle will be calculated as

$$\theta = (\Delta 1 + \Delta 2)/L \quad [11] \qquad \text{---------------------------- } 5.1$$

Figure 5.3: Test component

5.3 Experimental Results

5.3.1 Torsional stiffness for original wing

The original wing is tested for different loads reading from 5 Kg to 20 Kg while L = 1470 mm and the result is shown in Table (5.1)

Table (5.1) experimental torsional stiffness result for original wing

Load [Kg]	Torque [Nm]	Δ1 [mm]	Δ2 [mm]	θ [rad]
0	0	0	0	0
5	12.2625	2.3	2	0.002925
10	24.525	3.7	4.3	0.005442
15	36.7875	6.8	5.8	0.008571
20	49.05	9.9	7.5	0.011836

5.3.2 Torsional stiffness for redesigned wing

The redesigned wing is tested for different loads reading from 5 Kg to 20 Kg while L = 1470 mm. The result is represented in Table (5.2)

Table (5.2) experimental torsional stiffness result for redesigned wing

Load [Kg]	**Torque [Nm]**	**Δ1 [mm]**	**Δ2 [mm]**	**θ [rad]**
0	0	0	0	0
5	12.2625	1.6	1.2	0.001905

10	24.525	2.9	2.5	0.003673
15	36.7875	4.4	4.4	0.005986
20	49.05	6.3	5.5	0.008027

Chapter six

Results and Discussion

6. Results and Discussion

The analytical, computational and experimental results of the original and redesigned wings of (ZAGIL) will be demonstrated and discussed.

6.1 Analytical Results

6.1.1 Divergence speed

Table 6.1: Analytical divergence speeds for original and redesigned wings

Divergence speed for original wing [m/s]	**Divergence speed for redesigned wing [m/s]**
2026.5	894.9

This speeds is a theoretical speed and it doesn't mean that the wing will fail at these speeds, because it is values depend only on the elastic twist angle (when $\theta = \infty$)

6.1.2 Torsional stiffness

Table 6.2: Analytical torsional stiffness for original and redesigned wings

Torsional stiffness for original wing[m/s]	**Torsional stiffness for redesigned wing[m/s]**
5351	8162

The torsional stiffness represented by Table 6.2 for the redesigned wing is larger than for the original wing which means that the redesigned wing structure is stiffer than original wing.

6.2 Computational Results

6.2.1 Maximum vonmises stress

The Maximum vonmises stress for the skin and root of the original and redesigned wing is determined for angle of attack 12 degree and different Mach number as represented in Table 6.3 below.

Table 6.3: Maximum vonmises stress for original and redesigned wing

Part / Mach No	Skin [MPa]	Skin [MPa]	Root [MPa]	Root [MPa]
	Redesigned wing	Original wing	Redesigned wing	Original wing
M = 0.2	35.53	33.82	42.21	58.72
M = 0.4	142.14	101.62	168.84	176.46
M = 0.6	319.83	228.65	379.90	397.05
M = 0.7	435.32	311.22	517.08	540.43
M = 0.8	568.58	406.50	675.38	705.86

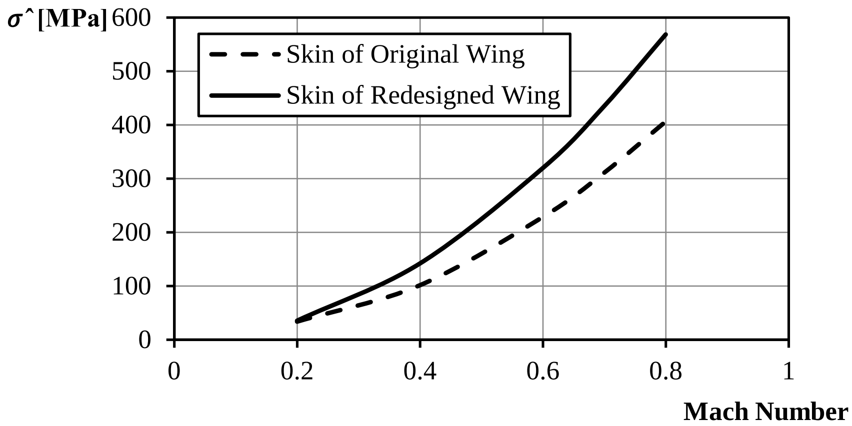


Figure 6.1: Maximum von Mises stress for Skin

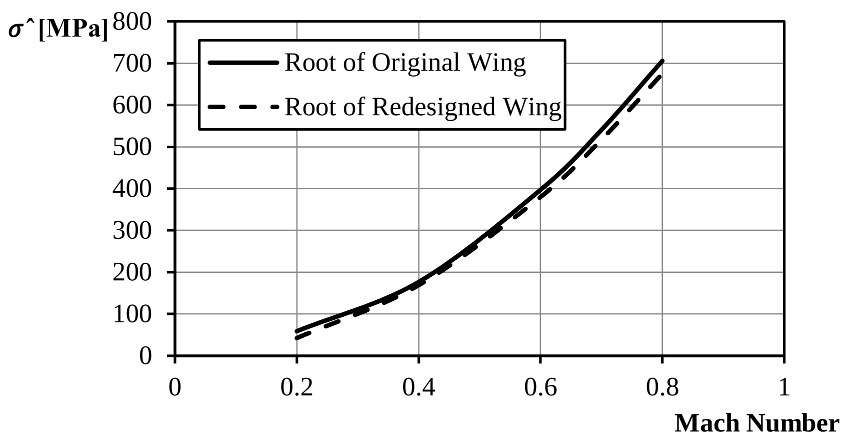


Figure 6.2: Maximum von Mises stress for Root

The maximum von Mises stress at skin for both, original and redesigned wings is gradually increase with Mach till 0.8 as represented by Figures 6.1. The maximum von Mises stress at skin for the redesigned wing is around 150 higher than the original skin at 0.8 Mach number. The maximum von Mises stress at Root for both, original and redesigned wings is satisfactory and representing the same results. This means the Root of the wing is not influenced by the redesign performed on the wing, but the Skin is only largely affected.

6.2.2 Torsional stiffness

Torsional stiffness is computed numerically for original and redesigned wing by applying two opposite forces such as in experimental test and the results is illustrated in Table 6.4

Table 6.4: Computational torsional stiffness for original and redesigned wing

Load [Kg]	**θ [rad] Original wing**	***θ* [rad] Redesigned wing**
0	0	0
5	0.002119	0.00138
10	0.004238	0.00276
15	0.006357	0.00414
20	0.008476	0.005519

6.2.3 Lift Force

Lift force is calculated by FEMAP and ANSYS fluent at AOA = 10.5 degree and Mach numbers 0.2, 0.4, 0.6, 0.8 and 0.95 as represented in Table 6.5.

Table 6.5: Lift force calculated by FEMAP and FLUENT

Mach	**Lift force [N] FEMAP**	**Lift force [N] FLUENT**
0.2	426	327.6
0.4	1700	1346.9
0.6	3840	3291.6
0.8	6820	6204.9
0.95	9490	7780.9

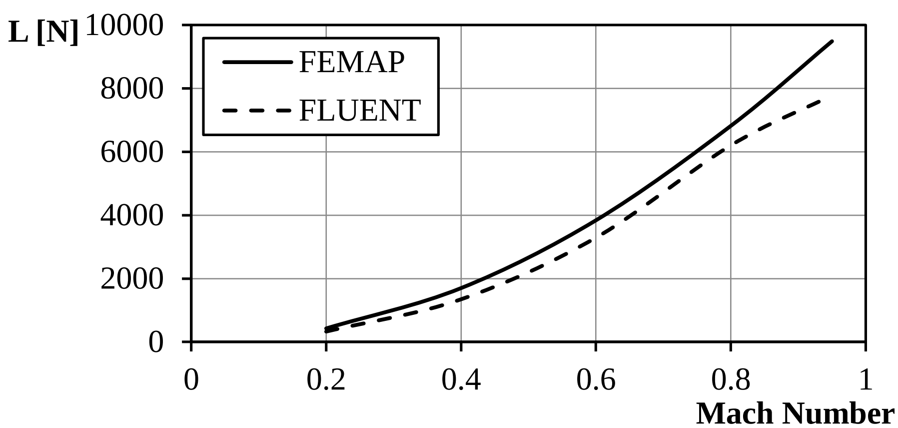


Figure 6.1: Lift force against Mach number

Figure 6.1 represents the lift force increment from Mach number 0.2 till 0.95. The result show very good agreement between both computational soft wares till Mach number 0.8 after that a little bit under-predicting is observed by Fluent software due to the capability of FLUENT software to capture the effect of shock wave.

6.3 Experimental Results

6.3.1 Torsional Stiffness

Table 6.6: Experimental torsional stiffness for original and redesigned wing

Load [Kg]	***θ* [rad] Original wing**	***θ* [rad] Redesigned wing**
0	0	0
5	0.002925	0.001905
10	0.005442	0.003673
15	0.008571	0.005986
20	0.011836	0.008027

6.4 Validation of torsional stiffness

Experimental exercise is carried out to validate the computational result of torsional stiffness for both, the original and redesigned wing.

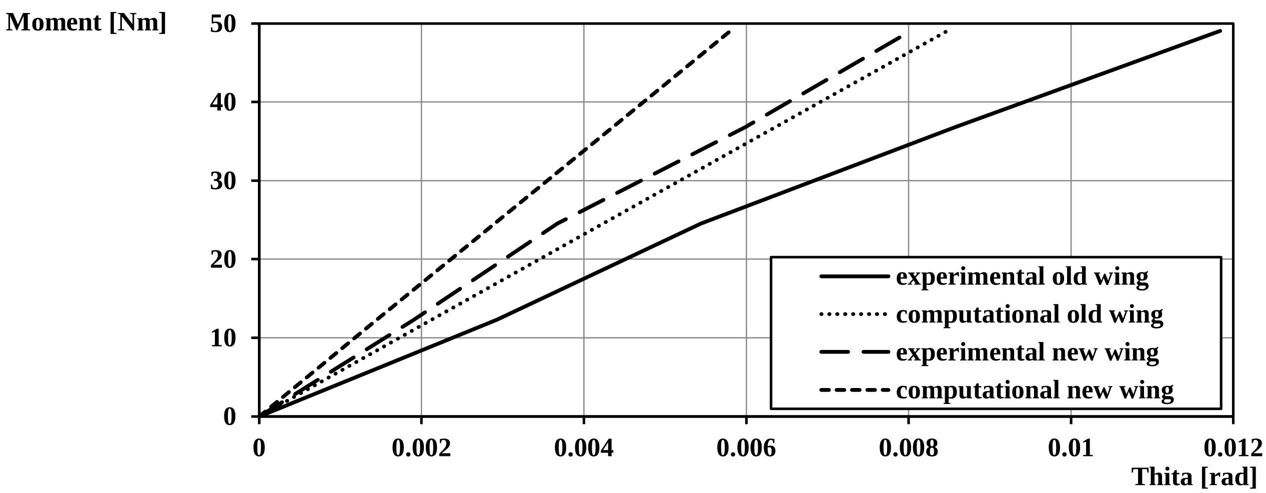


Figure 6.2: Experimental and computational stiffness for original and redesigned wing

Figure 6.2 shows the validation of computational result of torsional stiffness parameter for both, original and redesigned wing by conducted experimental tests. The numerical and experimental results for the redesigned wing represents that it is stiffer than the original wing.

Chapter seven

Conclusion and Recommendations

7.1 Conclusion

FEMAP aerodynamic results are confirmed by ANSYS FLUENT results and the difference between these two results is about 23%. FEMAP structural results (torsional stiffness results) are also confirmed by an experimental test results and the error between the results is about 20%.

The research explains that the redesigned wing is better than the original wing in torsional stiffness and divergence speed and the stress in the redesigned wing is much lower than in original wing especially in the wing root attachment zone.

Using the extrusion technology to manufacturing the redesigned wing, make the redesigned wing skin roughness less than the original wing which reveals in reduction of skin friction drag and thus enhances aerodynamic efficiency.

The manufacturing steps, time and cost of redesigned wing are obviously minimized by the virtue of extrusion technology.

7.2 Recommendation

It is obvious from obtained results the metallic wing reaches its limitation so using composite material can overcome the resulting stresses without affecting the wing weight.

If there is other technique than panel method that takes the shock wave phenomena and real shape of wing in consideration to calculate the lift forces, the result will be more accurate.

References

[1] Liviu Librescu and KaramY. Maalawi, "Aeroelastic design optimization of thin-walled subsonic wings against divergence", Science Direct, 47 (2009) 89– 97

[2] Wan Zhiqiang, Zhang Bocheng, Du Ziliang and Yang Chao, "Aeroelastic two-level optimization for preliminary design of wing structures considering robust constraints", Chinese Journal of Aeronautics, (2014), 27(2): 259–265

[3] Bret K. Stanford and Peter D. Dunning, "Optimal Topology of Aircraft Rib and Spar Structures Under Aeroelastic Loads", JOURNAL OFAIRCRAFT (2015), DOI: 10.2514/1.C032913

[4] Liviu Librescu and KaramY. Maalawi, "Aeroelastic design optimization of thin-walled subsonic wings against divergence", Science Direct, 47 (2009) 89– 97

[5] Dillinger J.K.S, M.M. Abdalla, T. Klimmek, Z. Gurdal, "Static Aeroelastic Stiffness Optimization and Investigation of Forward Swept Composite Wings", 10th World Congress on Structural and Multidisciplinary Optimization, 2013, Orlando, Florida, USA

[6] Scott Townsend, Renato Picelli, Bret Stanford, H. Alicia Kim, "Structural Optimization of Plate-like Aircraft Wings under Flutter & Divergence Constraints", AIAA Journal file, http://orca.cf.ac.uk/111081

[7] Yi Li and Tianhong Wang, "Interval analysis of the wing divergence", Aerospace Science and Technology, Science Direct, 74 (2018) 17–21

[8] Megson T.H.G, "Aircraft Structures for Engineering Students, Book", Fourth Edition, Linacre House, Jordan Hill, Oxford OX2 8DP, UK

[9] Changchuan Xie,1 Yang Meng,1 Fei Wang, and Zhiqiang Wan1 ,"Aeroelastic Optimization Design for High-Aspect-Ratio Wings with Large Deformation", Hindawi Shock and Vibration Volume 2017, Article ID 2564314

[10] YANG Chao, XIAO ZhiPeng, WAN ZhiQiang, YAN De & DAI YuTing ,Aeroelastic optimization design for wing with maneuver load uncertainties, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China ,November 2010 Vol.53 No.11: 3102–3109

[11] Rodney H. Ricketts,Structural Testing for Static Failure, Flutter, and Other Scary Things, National Aeronautics and Space Administration Langley Research Center Hampton, Virginia 23681–2199