ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS

CONCEPTUAL DESIGN AND CFD ANALYSIS OF AN UNMANNED HELICOPTER

GRADUATION PROJECT

Aykut ÜÇTEPE

Department of Aeronautical Engineering

Thesis Advisor: Prof. Dr. Alim Rüstem Aslan

JUNE, 2020

ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS

CONCEPTUAL DESIGN AND CFD ANALYSIS OF AN UNMANNED HELICOPTER

GRADUATION PROJECT

Aykut Üçtepe

(110150049)

Department of Aeronautıcal Engineering

Thesis Advisor: Prof. Dr. Alim Rüstem Aslan

JULY, 2020

Aykut ÜÇTEPE, student of ITU Faculty of Aeronautics and Astronautics student ID **110150049**, successfully defended the **graduation** entitled **"CONCEPTUAL DESIGN AND CFD ANALYSIS OF AN UNMANNED HELICOPTER"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Alim Rüstem ASLAN** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Fırat Oğuz EDİS** ....
İstanbul Technical University

Dr. Özge ÖZDEMİR ....
İstanbul Technical University

Date of Submission : 13 July 2020

Date of Defense : 22 July 2020

To my family,

FOREWORD

Thanks to my graduation project advisor Prof. Dr. Alim Rüstem Aslan for always supporting me and helping me. He helped with big patience whenever I feel desperate.

Also, I am extremely grateful for being the team leader of ITU Apis R&D for two years. We have participated in lots of competitions and learned how to be a family. I will never forget the championship in the US Cansat Competition 2019.

Finally, thanks to my family for supporting me throughout my education life.

July 2020 Aykut ÜÇTEPE

TABLE OF CONTENTS

Page

ABBREVIATIONS

CAD	: Computer Aided Design
CFD	: Computational Fluid Dynamics
DL	: Disc Loading
FM	: Figure of Merit
GSCO	: Ground Station Control Officer
HP	: Horsepower
MTOW	: Maximum Take-Off Weight
PL	: Power Loading
RPM	: Revolutions Per Minute
SFC	: Specific Fuel Consumption
SST	: Shear Stress Transport
UL	: Utility Load

LIST OF TABLES

Page

LIST OF FIGURES

Page

CONCEPTUAL DESIGN AND CFD ANALYSIS OF AN UNMANNED HELICOPTER

SUMMARY

In this thesis study, researches made to design a firefighter unmanned helicopter. The designed helicopter will be used to observe and extinguish the forest fires. The helicopter will drop fire extinguisher balls into the fire. After dropping balls, the helicopter will hover over the forest fire to collect data. The collected data will be sent to fire departments around the forest and other fire extinguisher helicopters. For this mission, both endurance and range are crucial. The aim of this mission is decreasing spread rate of the fire. Also, using unmanned systems in risky operations is a better option. Unmanned systems are helping to save human life.

Almost all steps of the unmanned helicopter design are iterative. The conceptual design process is started with estimations and continued with literature search and performance calculations. For each estimation, data collected from previous helicopters are taken into account. Key specifications of the design are maximum take-off weight, utility load, disc loading, power loading, engine power, figure of merit, rotor tip speed, power required and range. In addition, noise and vibration level are crucial for a successful design. Comparisons made between calculated performance parameters and estimated performance parameters. New estimations and calculations made until the calculated data and estimated data match with each other. After all calculations are made for sizing of the helicopter, 3D design of the helicopter is done using CATIA V5R19. Fuselage and rotor blades are designed using CATIA V5R19 Generative Shape Design module. Then, other mechanical parts are designed using Part Design module and designed parts are assembled on the fuselage. To made CFD analysis for the fuselage, boundary conditions are determined and changes made on the geometry to increase the mesh quality. Finally, CFD analysis is made for fuselage in forward flight condition to find the parasitic drag coefficient and drag created.

İNSANSIZ BİR HELİKOPTERİN KAVRAMSAL TASARIMI VE CFD ANALİZİ

ÖZET

Bu tezde, insansız bir helikopter üzerine kavramsal tasarım çalışması yapılmıştır. Tasarıma başlamadan önce helikopterin görevinin seçilmesi gerekmektedir, bu çalışmada helikopterin görevi yangın söndürme olarak belirlenmiştir. Helikopterler ormanlara yakın bölgelere kurulacak olan yer istasyonlarında saklanacaktır. Ormanlara yerleştirilen yangın detektörleri yangın tespit ettiğinde helikopterler bu alana müdahale etmek üzere gidecek ve yangın söndürme toplarını yangın alanının içerisine bırakacaklardır. Yer istasyonunda bulunan görevli helikopterin yakıt durumunu ve yangın söndürme toplarını kontrol edecektir. Yer istasyonu görevlisinin görevi başlatmasının ardından helikopter yangın alanına doğru yola çıkacaktır. Helikopter yangın alanının üzerine geldiğinde termal kamera yardımı ile alanı tarayacak ve yangındaki en sıcak noktayı bulacaktır. En sıcak noktanın tespit edilmesinin ardından yangın söndürme topları bu noktaya isabet edecek şekilde bırakılacaktır. Helikopter bu evreden sonra 2 saat boyunca yangın üzerinde gözlem uçuşu yapacak ve topladığı verileri hem diğer insansız helikopterlere hem de itfaiye istasyonlarına göndererek yangınının kontrol altına alınmasına yardım edecektir. Gözlemin ardından helikopter yer istasyonuna geri dönecektir.

Görevi gerçekleştirmek için klasik helikopter tipinin kullanılmasına karar verilmiştir. Multikopter tipi günümüzde ne kadar popüler olsa da bu görev için gerekli koşulları sağlamamaktadır. Multikopterler 4 veya daha fazla küçük boyutlu pervane bulundururlar. Helikopterler ise 1 adet büyük boyutlu pervane bulundurur. Taşıma üretimi alanla doğru orantılı olduğu için aynı RPM değerinde helikopterler multikopterlere göre daha fazla lift üretirler. Multikopterlerin daha yüksek RPM değerinde çalışarak lift üretmesi daha fazla güç harcanmasına neden olacaktır. Bu yüzden, helikopterler multikopterlere göre daha yüksek güç verimine sahiptir. Ayrıca helikopterler rotor palalarının açılarını değiştirebildikleri için kötü hava koşullarında multikopterlere göre daha dengelerini daha kolay korurlar. Rotor palalarının açılarının değiştirilebilmesi aynı zamanda helikopterin ileri uçuş hızının artmasına da yardımcı olmaktadır.

Konsept tasarım iteratif bir süreçtir. Yapılan tahminler ile bu tahminlere bağlı olarak yapılan hesaplamalar birbirini karşılayana kadar tahminlere ve hesaplamalara devam edilmektedir. Tahminlere başlamadan önce payload kütlesi belirlenmelidir. Payload ise helikopterin taşıma kapasitesi olarak tanılandırılır. Bu görevde payload 6 adet yangın söndürme topu, termal kamera, top taşıma mekanizması ve elektronik elemanlardır. Payload ağırlığı hesaplandıktan sonra önceden yapılan helikopterlerin faydalı yük miktarları, motor güçleri ve maksimum kalkış ağırlıkları incelenmelidir. Tahmini bir motor gücü seçilmeli ve yakıt miktarı hesaplanmalıdır.

Payload kütlesi ile yakıt kütlesinin toplamı, faydalı yüke eşittir. Önceden yapılan helikopterlerin verileri üzerinden 2020 yılında faydalı yükün maksimum kalkış ağırlığına oranı bulunmuştur. Faydalı yükün bu orana bölümü, en başta tahmin edilen maksimum kalkış ağırlığını sağlayana kadar tahminler ve hesaplamalar yapılmaya devam etmiştir. Maksimum kalkış ağırlığı kavramı kg ya da N cinsinden belirtilmektedir.

Maksimum kalkış ağırlığının bulunmasının ardından rotor alanını hesaplayabilmek için önceden üretilen helikopterlerin disc loading ve maksimum kalkış ağırlıkları incelenmiştir. Disc loading bulunduktan sonra rotor alanı ve rotor yarıçapı hesaplanmıştır.

Tahmin edilen motor günün sağlamasının yapılması için önceden üretilen helikopterlerin ağırlığının motor gücüne oranı(power loading) verileri ve maksimum kalkış ağırlıkları incelenmiştir. Kabul edilen maksimum kalkış ağırlığına denk gelen power loading değeri bulunmuştur ve motor gücü hesaplanmıştır.

Helikoptere ait boyutlandırma hesaplamaları yapıldıktan sonra, CATIA V5R19 programı kullanılarak bir helikopter gövdesi tasarlanmıştır. Bu gövde tasarlanırken sürükleme kuvvetinin olabildiğince az olmasına ve gövdenin tüm elemanları içerisine sığdırabilmesi ana tasarım hedefleri olmuştur.

Helikopterin uçuşun farklı evrelerinde harcayacağı güç miktarı, tüketilecek yakıt miktarı ve menzil hesaplanıştır. Bu hesaplamaların görev isterlerini karşıladığı tespit edilmiştir. Ardından, helikopterin bu hesaplamalarda bulunan değerleri sağlayabilecek kapasitede olup olmadığı kontrol edilmiştir. Tüm kontroller yapıldıktan ve tüm eşitlikler birbirini sağladıktan sonra konsept tasarım kısmı tamamlanmıştır.

Tasarlanan gövdenin ileri uçuş şartlarında ANSYS Fluent modülü üzerinde CFD analizi yapılmıştır.

1. INTRODUCTION

Forests are crucial for the survival of the people and animals. Moreover, being habitats for animals and livelihoods for humans, forests help to reduce the risk of climate change and prevent soil erosion. But unfortunately, forests are disappearing because of the fires. In 2019 massive forest fires occurred in Australia, Brazil, Russia, and India. Also, minor forest fires were common all around the world.

Forest fires are naturally caused or human-caused. Natural reasons are mostly lightning. On the other side, generally, the reasons for the human-caused fires are smoking and recreation [1].

It is impossible to estimate a forest fire before it starts. However, forest fires can be detected just after it starts. As the detection time becomes shorter, the chance of preventing forest fire increases. In this thesis, a fire detection system and a fire extinguisher helicopter designed.

1.1 Mission

An autonomous fire detection system will be established in the forests. If the system detects a fire, ground stations will be warned. Ground station control officer (GSCO) will control fire extinguisher balls and fuel in the helicopter. After GSCO confirms the helicopter is ready, the helicopter will takeoff autonomously. When the helicopter arrives at the fire area, it will detect the location with the highest temperature using its thermal camera and image processing. The helicopter will drop the fire extinguisher balls on to the areas with the highest temperature. After dropping the balls, the helicopter will observe the area and sent data about the fire to other helicopters and fire departments.

Helicopter ground stations will be established near the forests. So, helicopters will be able to arrive at the fire area after a maximum 30 minutes of forward flight. After the helicopter drops the fire extinguisher balls, the helicopter will hover over the fire area for 2 hours to scan the area and collect information about the fire. To escape from negative effects from the smoke rise from the fire, helicopter will hover at 1 km altitude.

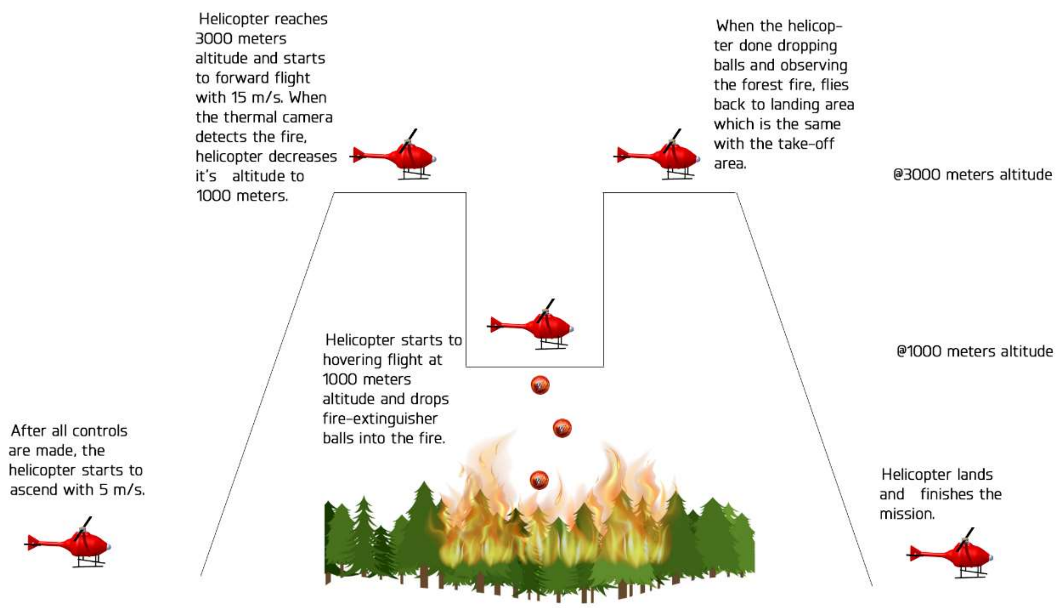

Figure 1.1 : Mission Profile.

2. CONCEPTUAL DESIGN

Conceptual design is an iterative process. The process starts with the determination of the mission requirements and continues with a literature search and calculations [2].

The mission of the helicopter is selected as firefighter. To achieve this mission, the unmanned helicopter needs to carry fire extinguisher balls and drop them into the fire. After selecting the quantity of the fire extinguisher balls, other parts of the payload are taken account and total payload mass is found. Utility load, maximum takeoff weight, rotor diameter, engine power, year of production data are collected from previous unmanned helicopters. Using collected data, estimations are made for MTOW and engine power. Then, the estimations are involved in calculations, and convergence is checked until the estimations satisfy the calculations. Subsequently, disc loading, power loading, main rotor diameter, engine power, tail rotor diameter, tail rotor arm, fuel mass-consumed, range covered and required power are calculated.

Finally, in the scope of the calculations made, the unmanned helicopter is 3D designed and CFD analysis is made for the fuselage to evaluate the aerodynamic performance of the helicopter.

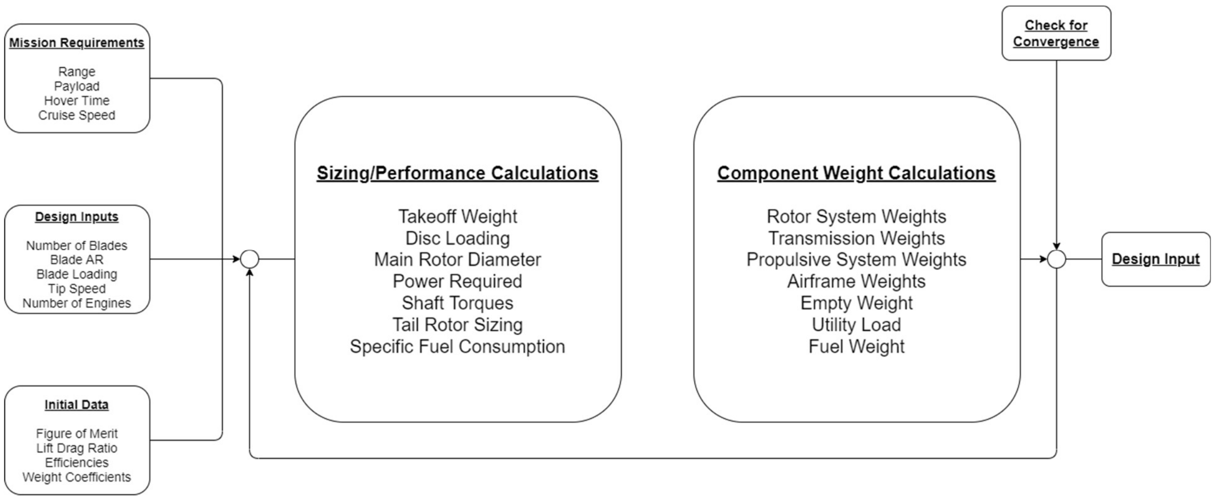

Figure 2.1 : Conceptual Design Flowchart.

2.1 Literature Search

Researchs are made between unmanned helicopters. Collecting data from previous helicopters helps to make more correct estimations at the start of the unmanned helicopter design study.

Table 2.1 : Specifications of the Unmanned Helicopters.

Helicopter Model	MTOW (kg)	Rotor DIameter (m)	UL (kg)	UL/GW	YEAR
FT-200 FH [3]	80	2.8	50	0.625	2016
Northrop Grumman MQ-8 [4]	1430	8.4	490	0.342657343	2009
Ziyan Blowfish [5]	25	1.88	15	0.6	2017
VRT300 [6]	300	not given	165	0.55	2019
Georgian Black Widow [7]	680	7.62	238	0.35	2015
UMS V-200 [8]	235	4.6	40	0.170212766	2013
Yamaha rmax [9]	94	3.115	30	0.319148936	1995
Schiebel Camcopter	200	3.4	131	0.655	2006
Ka-137 [10]	280	5.3	80	0.285714286	1998
Aeroscout B1-100 [11]	77.00	3.2	27	0.350649351	2016
Alpha 800 [12]	14	1.8	3	0.214285714	2017
Uavos R22 [13]	635	7.7	220	0.346456693	2019
Airbus Tanan [14]	350.00	5	80	0.228571429	2019
UMS V-150 [15]	150	3.5	55	0.366666667	2020
UVH-290E [16]	107	3.2	34	0.317757009	2018
UVH 25EL [17]	25	2.6	5	0.2	2019
R-Bat [18]	95	3.13	19.5	0.205263158	2014
Challis E-950 [19]	25	2.08	15	0.6	2012
FT-100 FH [20]	12.00	1.30	5	0.416666667	2018
VSR700 [21]	700	7.2	250	0.357142857	2018
Boeing A160 [22]	2948	11	1814	0.615332429	2012
Gyrodyne QH-50 DASH [23]	1035	6.1	510	0.492753623	1963
KAI / Boeing KUS-VJ [24]	1300	8.03	700	0.538461538	2025
Rapier Unmanned	350	5	155	0.442857143	2015
Aeroscout B330 [25]	140	4	62	0.442857143	2019
Awhero Unmanned [26]	205	4	85	0.414634146	2019
Northrop Grumman MQ-8B [27]	2721	11.2	1338	0.491730981	2013
SDO 50 V2 [28]	87	2.82	45	0.517241379	2019

2.2 Advantages of Conventional Helicopters over Multicopters

Multicopters have been used frequently in recent years by the cause of being mechanically simpler and cheaper than helicopters. The main areas where multicopters are used are aerial photography, racing, and light goods delivery. On the other side, conventional helicopters are preferred owing to their higher endurance, higher stability, and higher power efficiency.

Lift increases as the blade area increases. Conventional helicopters have one big main rotor while multicopters have small-sized four or more propellers. To produce the same amount of lift, smaller propellers need to rotate at much higher RPM values. Thus, energy is wasted and power efficiency is decreased in multicopters [29].

Contrary to multicopters, helicopters have the ability to change their blade’s angle of attack during the flight. As a result of this ability, helicopters can adapt the environmental conditions more easily and helicopters are more stable in bad weather conditions. In addition, changing the blade’s angle of attack helps to increase forward flight speed. With higher forward flight speeds, helicopters can fly to higher ranges than multicopters.

Table 2.2 : Helicopter – Multicopter Comparision Table.

	Multicopter	Conventional Helicopter
Higher Hover Efficiency		✓
Lower Cost	✓	
More Range		✓
Less Mechanical Complexity	✓	
More Stable in Bad Weather		✓
Higher Forward Flight Speed		✓

In this design study, carrying more payload, having high cruising speed, and covering more area is crucial for the success of the mission. Thus, type of the aircraft is selected as a conventional helicopter.

2.3 Payload

Payload is the carrying capacity of an aircraft. Mission equipment, passengers and cargo are considered as the payload.

In this mission, because the helicopter is unmanned, no passengers and flight crew are needed. Payloads of the helicopter are 6 fire extinguisher balls, ball carrying mechanism, thermal camera, and avionics. Payload specifications are given in the table below:

Table 2.3 : Payload Mass Table.

Part	Mass (kg)
Fire Extinguisher Ball (6 pcs)	9
Thermal Camera	0.325
Ball carrier system	2.5
Electronics (Sensors,Autopilot, PCB)	1.5
Adhesives etc.	0.675
TOTAL:	14

Figure 2.2 : Fire Extinguisher Ball.

2.4 MTOW Determination Process

To determine maximum take-off weight (MTOW), the rate of utility load (UL) to MTOW must be found using literature search.

Firstly, UL, MTOW and production year data for each helicopter are collected. Then, data marked as dots for each helicopter on a (UL/MTOW)-PRODUCTION YEAR graph. A correlation line is plotted between the dots and the average rate of UL/MTOW for the 2020 is found as 0.4. To design more efficient helicopter than previous ones, UL/MTOW is taken as 0.5 which is slightly higher than the average value.

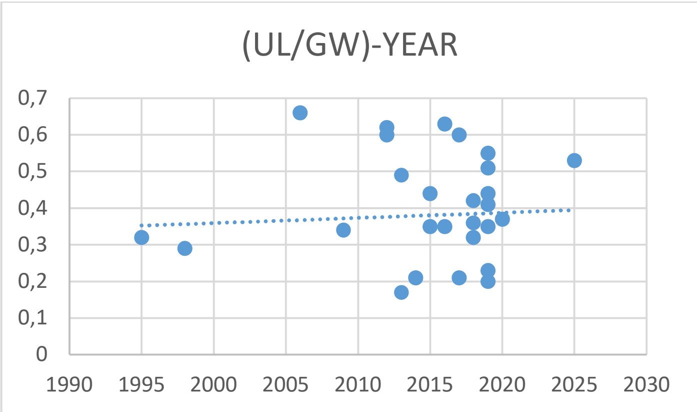

Figure 2.3 : UL/GW Estimation Graph.

For unmanned helicopters, utility load (UL) is equal to the sum of the mass of payload and fuel. Mass of the payload is already calculated as 14 kilograms. To calculate fuel mass, power of the engine must be estimated in horsepower [30]. For this mission, an engine with 20 hp is selected. Also, specific fuel consumption (SFC) is taken 0.5 for the piston engines. In order to achieve a 3 hours mission, fuel mass and utility load are calculated as given below. Thirty minutes are added to mission time due to reserve fuel.

$$Fuel\ mass\ (in\ lb) = SFC * hp * Mission\ time(hour) \tag{2.1}$$

$$Fuel\ mass = 0.5 * 20 * 3.5 = 52.5\ lbs = 15.87\ kg$$

$$Utility\ Load(UL) = Payload + Fuel \tag{2.2}$$

UL = 14 + 15.87 = 29.87 kg

UL/GW ratio is taken as 0.5 for 2020, MTOW is two times of UL and equal to 59.74 kg. This value is rounded to 60 kg and it is accepted as MTOW.

2.5 Main Rotor Design

Disc loading(DL) is defined as the rate of weight to main rotor area and measured in Newtons per square meter or kilograms per square meter. In this thesis, disc loading is measured in kilograms per square meter (kg/m^2). [2]

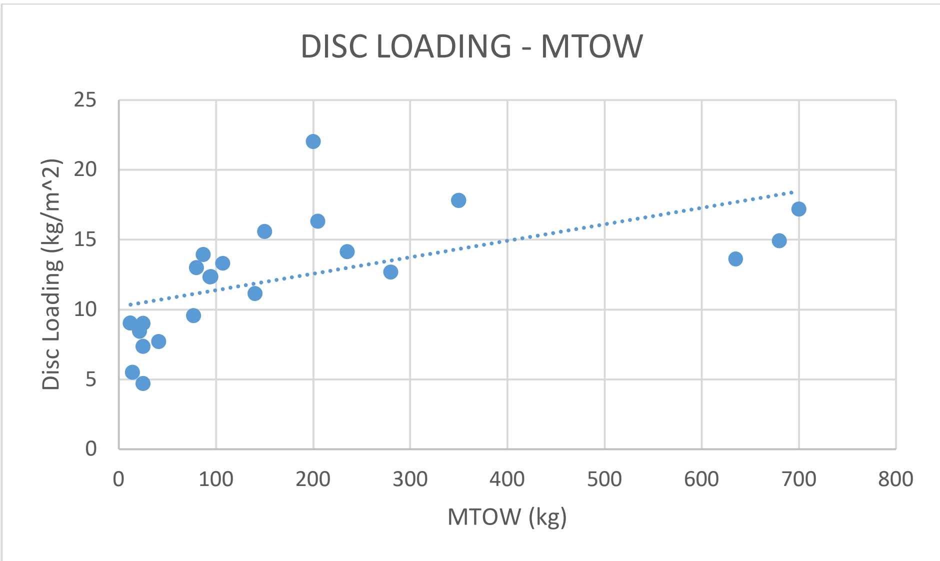

Figure 2.4 : Disc Loading Estimation Graph.

Disc loading and MTOW data from the unmanned helicopters collected and a Disc Loading – MTOW graph is plotted. A fitting line is drawn between the data in the graph. As a result, for 60 kg MTOW, the disc loading is found over 10 kg/m^2. In order to design a more efficient helicopter, the disc loading is taken as 15 kg/m^2. To satisfy 15 kg/m^2

disc loading, main rotor disc diameter is calculated as 2.25 meters. It is decided to use 2 rotor blades in order to ensure weight advantage.

$$Disc\ Loading(DL) = \frac{MTOW}{Main\ Rotor\ Area} \quad \textbf{(2.3)}$$

$$15\ \frac{kg}{m^2} = \frac{60\ kg}{Main\ Rotor\ Area}$$

Main Rotor Area = 4 m^2

Main Rotor Diameter = 2.257 m

2.6 Engine Selection

Power loading (PL) is the rate of MTOW to engine power. PL can be written in lb/hp or kg/KW. [2]

As it is mentioned before, nearly all of steps of the conceptual design is iterative. Engine selection process is also iterative. In fuel mass calculation section, engine power is estimated as 20 hp. So, the engine power found by Power Loading – Disc Loading graph must satisfy 20 hp.

Firstly, power loading and disc loading data are collected from the produced unmanned helicopters. Then, for each helicopter these data are marked as dots on a power loading – disc loading graph. A fitting line is plotted between the dots and appropriate power loading with respect to 15 kg/m^2 is found as 4.2 kg/hp. Considering the estimated MTOW is 60 kilograms, the required engine power is found as 13.95 hp.

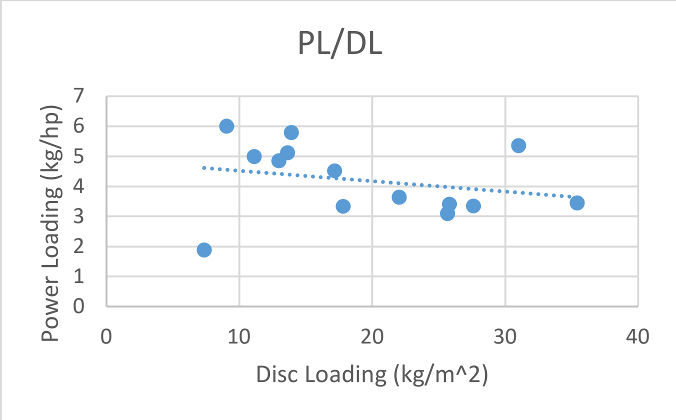

Figure 2.5 : Power Loading – Disc Loading Graph.

In real life conditions, always efficiency loss takes place. Figure of merit is used to measure the system efficiency . Figure of merit is generally between 0.5 and 0.8 [2]. Figure of merit is accepted as 0.7 for this design. First estimation is 20 hp and it satisfies required engine power for the helicopter.

$$Figure\ of\ Merit\ (FM) = \frac{Actual\ Condition}{Perfect\ Condition}. \tag{2.4}$$

$$Required\ Engine\ Power = \frac{Estimated\ Engine\ Power}{FM} = \frac{13.95\ hp}{0.7} = 20\ hp$$

Figure 2.6 : Limbach L 275E.

After the calculations and researches are done, Limbach L 275E is selected as engine. Specifications of the engine are given in the table below.

Table 2.4 : Specifications of Limbach L 275E.

Dry Weight (kg)	7,2
Power (hp)	20
Fuel	AVGAS 100LL
Strokes	2
Cylinders	2
Displacement (cm^3)	274

2.7 Fuselage Design

Fuselage is body of the helicopter. Payload, fuel tanks and engine are carried inside the fuselage. Also, fuselage connects the crucial mechanical parts to each other.

Apart from being an important structural part of the helicopter, shape of fuselage effects the aerodynamic performance of the helicopter heavily.

In this design study, the aim is to reduce the flat plate area of the helicopter as much as possible. Other key requirement is the ensuring enough space for the engine, payload, fuel tanks and mechanical parts. The fuselage is designed considering these requirements using CATIA V5 Generative Shape Design module. A gimbal system with thermal camera is placed in front of the fuselage. Fire extinguisher balls are placed beneath the fuselage.

Figure 2.7 : Fuselage of the Unmanned Helicopter.

3. PERFORMANCE CALCULATIONS

In order to complete the given mission successfully, performance calculations must made. The designed helicopter needs to ensure power requirements for hovering flight and forward flight. Also, consumed fuel mass is calculated and compared with the fuel mass taken in the start of conceptual design study.

3.1 Speed For Maximum Range

Range is the maximum distance the helicopter can take with available fuel. Forward flight speed is one of the most important criteria for the range covered. The forward flight speed to cover maximum range is calculated as below. [2]

$$V_{mr} = V_h\left(\frac{4\kappa}{f/A}\right)^{1/4} = \sqrt{\frac{W}{2\rho A}}\left(\frac{4\kappa}{f/A}\right)^{1/4} \tag{2.5}$$

$$V_{mr} = \sqrt{\frac{588.6N}{2(0.9093\frac{kg}{m^3})4m^2}}\left(\frac{4(1.15)}{1/4}\right)^{1/4} = 18.61\ m/s$$

3.2 Speed for Maximum Endurance

Endurance is defined as the maximum flight time of the helicopter. For the selected mission in this conceptual design study, high endurance is crucial. Forward flight speed also effects the endurance. The forward flight speed for achieving maximum endurance is calculated as below. [2]

$$V_y = V_h\left(\frac{4\kappa}{3f/A}\right)^{1/4} = \sqrt{\frac{W}{2\rho A}}\left(\frac{4\kappa}{3f/A}\right)^{1/4} \quad \textbf{(2.6)}$$

$$V_{mr} = \sqrt{\frac{588.6N}{2(0.9093\frac{kg}{m^3})4m^2}}\left(\frac{4(1.15)}{3/4}\right)^{1/4} = 14.147\ m/s$$

3.3 Power Required For Hovering Flight

Hover is the condition of flight which is the helicopter has no forward speed. In this mission, hover is too important because fire extinguisher balls will be deployed in hover condition. In addition, the helicopter will hover over the forest fire to observe the fire. During forest fires, the smoke rising from forest may affect helicopter and the camera negatively. To avoid the negative effects of the smoke, hovering altitude is determined as 1 kilometer.

$$\rho_{@1000m} = 1.112\ kg/m^3$$

$$P_{ideal} = \frac{W^{3/2}}{\sqrt{2\rho A}} \quad P_{hover} = \frac{P_{ideal}}{FM} \quad \textbf{(2.7)}$$

$$P_{ideal} = \frac{(588.6\ N)^{3/2}}{\sqrt{2(1.112\frac{kg}{m^3})(4m^2)}} = 4.788\ kW$$

$$P_{hover} = \frac{4.788\ kW}{0.7} = 6.84\ kW$$

3.4 Power Required For Forward Flight

In order to calculate the power required for forward flight, induced power, blade profile power, parasitic power and climb power must be calculated. Sum of the blade profile power and induced power is equal to power required for hover at the altitude of forward flight. Flat plate area is used instead of the reference area to avoid uncertainty of the value of the reference area. Flat plate area(f) is between 0.93 to 4.65 m^2. Since the helicopter designed for this mission is a small sized helicopter, the flat plate area is taken as $1m^2$. [2]

$$f = C_{D_f} S_{ref} = 1m^2$$

Forward flight speed is determined as 15 m/s to increase endurance of the helicopter. Also, altitude for forward flight is determined as 3000 meters to achieve power efficiency.

$$\rho_{@1000m} = 1.112\ kg/m^3$$

$$P_{forward\ flight} = P_o + P_i + P_p + P_c \quad \textbf{(2.8)}$$

$$f = C_{D_f} S_{ref} = 1m^2 \quad \textbf{(2.9)}$$

$$P_o + P_i = P_{hover@3000m} = \frac{1}{FM}\frac{T^{3/2}}{\sqrt{2 * \rho_{@3000m}A}} = 7.564\ kW \quad \textbf{(2.10)}$$

$$P_P = (\tfrac{1}{2}\rho {V_\infty}^3 f) = 1.534\ \text{kW} \quad \textbf{(2.11)}$$

$$P_c = WV_c = 2.943\ kW \quad \textbf{(2.12)}$$

$$P_{forward\ flight} = 7.654\ kW + 1.534\ kW + 2.943\ kW = 12.131\ kW$$

3.5 Calculation For Fuell Mass Consumed

At the start of the conceptual design study, the fuel mass is estimated as 15.94 kg. To complete the mission, the mass of fuel consumed during the mission must not exceed the fuel mass available. For each flight condition, the specific fuel consumption of the engine is found from the engine manual. In order to calculate fuel mass required for each phase of the flight, phase time must multiplicated by SFC and power needed for the phase. [2]

$$mass\ of\ the\ fuel\ consumed = Power\ needed * Flight\ Time * SFC \qquad \textbf{(2.13)}$$

3.5.1 Fuel Consumed During Hovering Flight

For hovering flight, the power needed is found in the previous sections. The SFC value regarding to the required power is found from the datasheet of the engine.

$$SFC_{hov} \quad = 340\ g/kWh$$

$$mass\ of\ the\ fuel\ consumed = 6.84kW * 2h * 340\frac{g}{kWh} = 4.65\ kg$$

3.5.2 Fuel Consumed During Forward Flight

For forward flight, the power needed is found in the previous sections. The SFC value regarding to the required power is found from the datasheet of the engine.

$$SFC_{forwardfligh} \quad = 530\ g/kWh$$

$$mass\ of\ the\ fuel\ consumed = 12.131kW * 1h * 530\frac{g}{kWh} = 6.429\ kg$$

3.6 Range Calculation

Range of the helicopter is equal to multiplication of forward flight time by forward flight speed. The forward flight time for this mission is half an hour.

$$Range = Forward\ Flight\ Speed * Phase\ Time = 15\frac{m}{s} * 1800\ s \qquad \textbf{(2.14)}$$

$$= 27\ \text{km}$$

3.7 Tail Rotor Design

Tail rotor is used to eliminate the torque created by the main rotor. If the torque created by main rotor is not eliminated, the helicopter will start to turn around itself. In this design study tail rotor diameter is found using the historical data. The tail rotor arm is calculated using the main rotor torque, tip speed and thrust. Tip speed of the main rotor and tail rotor must not exceed the speed of sound at the flight altitude in order to avoid from sonic boom.

3.7.1 Tail Rotor Diameter

The main rotor disc loading is selected as 15 kg/m^2 which is equal to 3.07 lb/ft^2. Tail rotor diameter/main rotor diameter ratio is taken as 0.16. Thus, tail rotor diameter is calculated as 0.36 m. [30]

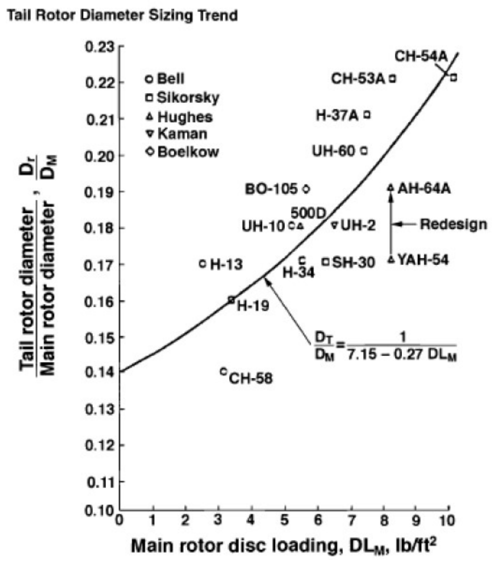

Figure 3.1 : Rotor Disc Sizing Trend.

$$\frac{Tail\ Rotor\ Diameter}{Main\ Rotor\ Diameter} = 0.16$$

$$\frac{Tail\ Rotor\ Diameter}{2.25\ m} = 0.16$$

Tail Rotor Diameter = 0.36 m

Tail Rotor Area = 0.102 m^2

3.7.2 Tail Rotor Moment Arm Calculation

The torque created by main rotor must be neutralized by tail rotor, otherwise the helicopter will start to rotate. The torque created by main rotor is calculated using the required thrust and power during the hovering flight. [2]

$$P_{required\ hover} = 6.84\ kW$$

After finding required power, angular velocity of the main rotor must be found. To find the angular velocity, thrust coefficient of the main propeller is determined and involved in the thrust equation.

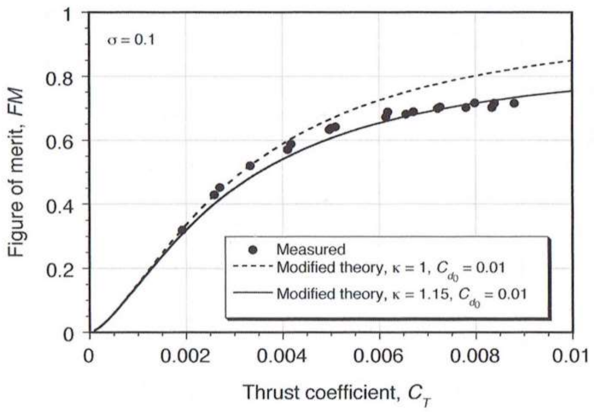

Figure 3.2 : FM – Thrust Coefficient Graph.

Thrust coefficient(c_T) is found as 0.008 for FM = 0.7 from the graph.

$$Thrust = T_{mr} = c_T * \rho_{@1000m} * A_{mr} * {\Omega_{mr}}^2 * {R_{mr}}^2 \qquad \textbf{(2.15)}$$

$$Thrust = T_{mr} = 588.6\ \text{N} = (0.008\,) * \left(0.9093\frac{kg}{m^3}\right) * (4\,m^2) * {\Omega_{mr}}^2 * {R_{mr}}^2$$

$$V_{tip\ main\ rotor} = \Omega * R_{mr} = 142.22\ m/s \qquad \textbf{(2.16)}$$

Rotor tip speed is under the speed of the sound at 1000 meters altitude. Thus, this angular velocity is appropriate for a safe flight.

Torque of the main rotor is equal to the rate of required power to angular velocity of the main rotor. After calculating the torque of the main rotor, thrust produced by tail rotor must be calculated. The multiplication of tail rotor thrust and tail rotor arm must be equal to the main rotor thrust.

	$$\Omega_{mr} = \frac{V_{tip\ main\ rotor}}{R_{mr}} = 126.42\ rad/s$$	**(2.17)**
	$$Torque = \frac{P_{required}}{\Omega_{mr}}$$	**(2.18)**
	$$Torque\ of\ the\ Main\ Rotor\ = Q_{mr}\ = \frac{P_{required}}{\Omega} = \frac{6.84\ kW}{126.42\frac{rad}{s}}$$ $$= 53.87\ N * m$$	**(2.19)**

While designing the fuselage, the tail rotor arm(x) is taken as 1 meter.

$$Thrust\ of\ Tail\ Rotor = \frac{Q_{mr}}{x} \tag{2.20}$$

$$Thrust\ of\ Tail\ Rotor = T_{tr} = \ c_T *\ \rho_{@1000m} * A_{tr} *\ {\Omega_{tr}}^2 * {R_{tr}}^2 \tag{2.21}$$

$$Thrust\ of\ Tail\ Rotor\ = 53.87\ \mathrm{N}$$

$$V_{tip\ tail\ rotor} = \ {\Omega_{tr}}^2 * {R_{tr}}^2 = 269.73\ m/s \tag{2.22}$$

Since the tail rotor tip speed is below the sound of speed at 1000 meters altitude, 1 meter tail rotor arm is appropriate for this design study.

4. CFD ANALYSIS

4.1 Method of the Analysis

In this thesis study, the CFD analysis is done using Fluent module of the ANSYS 2019 R3. 3D models can be analyzed using different methods. The methods used for analyzing the body are defined in this section.

Firstly, the 3D model is imported into DesignModeler which is a module of ANSYS 2019 R3. After, using *Enclosure* command a box is created around the model. *Boolean operations* are used to substract the model from the box. Then, named selections created for walls, inlet and outlet.

Before the analysis, simplifications made on the fuselage in order to increase the mesh quality. The simplified body is used for meshing and inflation command is used to create boundary layer around the body.

Lastly, boundary conditions and solution methods are defined. The drag and parasitic drag coefficient are found.

4.2 Meshing

To analyze fluid flows, surface of the 3D model is split into smaller parts. The fluid flow equations are solved inside this little parts using the boundary conditions for each part. The small surface parts are called as elements and the sum of the elements are called as mesh.

The quality of the mesh plays a significant role in the accuracy and stability of the numerical computation. The shape of the element affects the quality of mesh. Skewness is the difference between the shape of the cell and the shape of an equilateral cell of equivalent volume. Highly skewed cells can decrease accuracy of the solution. The average rate of the skewness must be under 0.33 and the maximum skewness must be under 0.95. Also, aspect ratio and orthogonality are other key considerations for the mesh quality. [31]

Boundary layer is created with respect to first layer thickness. First layer thickness is found as 10^{-5} meters and maximum layer number is found as 29.

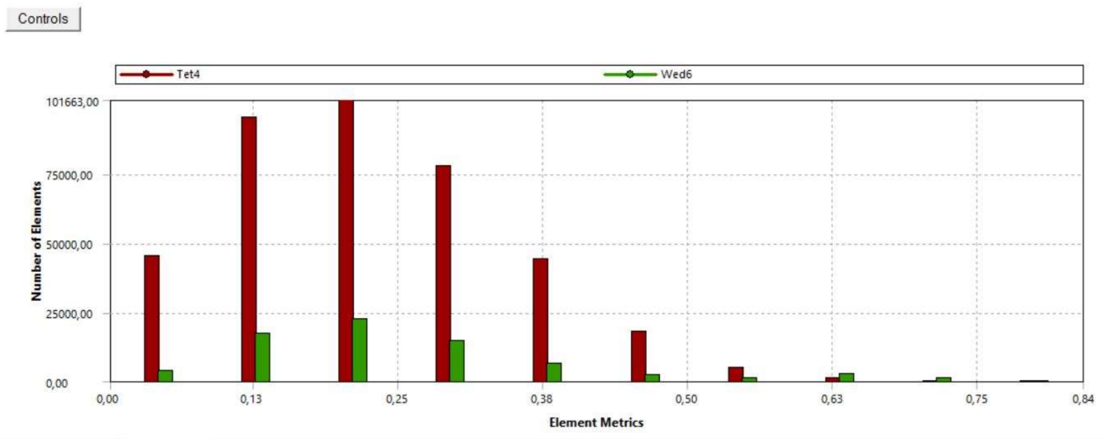

Figure 4.1 : Number of Elements – Skewness Graph.

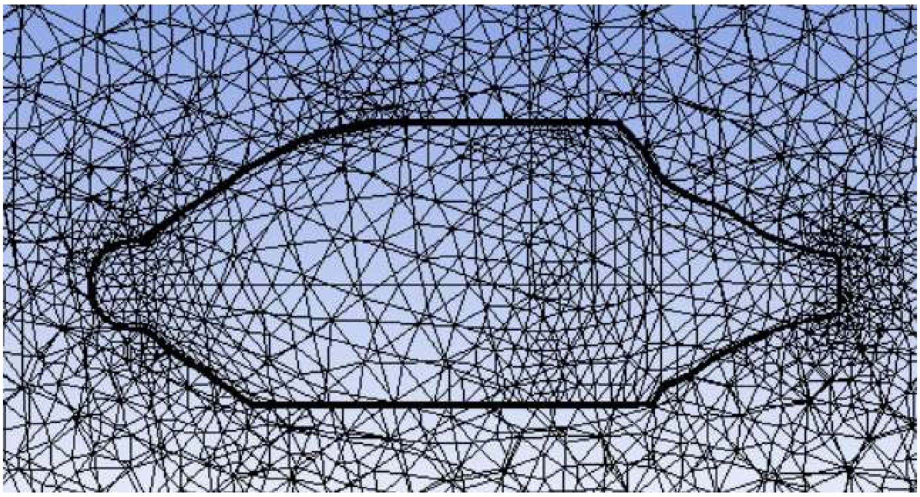

Figure 4.2 : Fuselage Meshing.

4.3 Boundary Conditions

Boundary conditions are determined in the conceptual design study. Airspeed is taken as 15 m/s and the air density is taken as 0.9093 kg/m^3 which is the air density at 3000 meters altitude.

Turbulence model is selected as SST k-omega in order to have good results at low Reynolds numbers. The k-omega model is well suited for simulating flow in the viscous sub-layer.

4.4 Results

After the analysis, Wall y+ value is checked. The desired value of y+ is smaller than 1. The maximum wall y+ value is found as 0.455 and the drag of the fuselage is found as 28.44 N. Surface area of the fuselage is found as 1.34 m^2. Drag coefficient is calculated as 0.21.

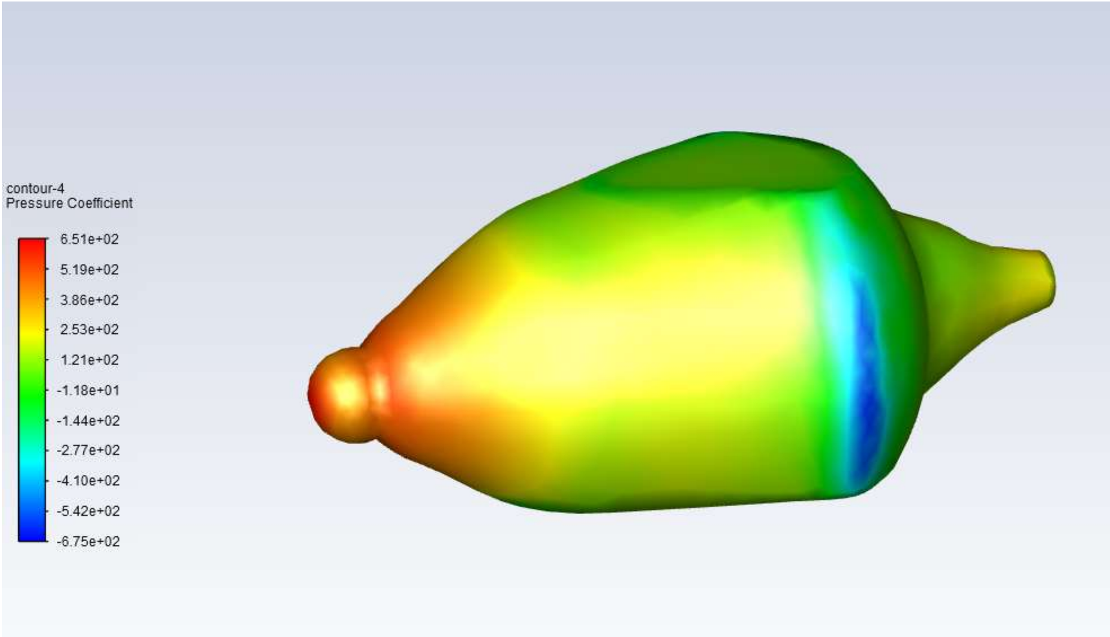

Figure 4.3 : Pressure Coefficient Distribution over the Fuselage**.**

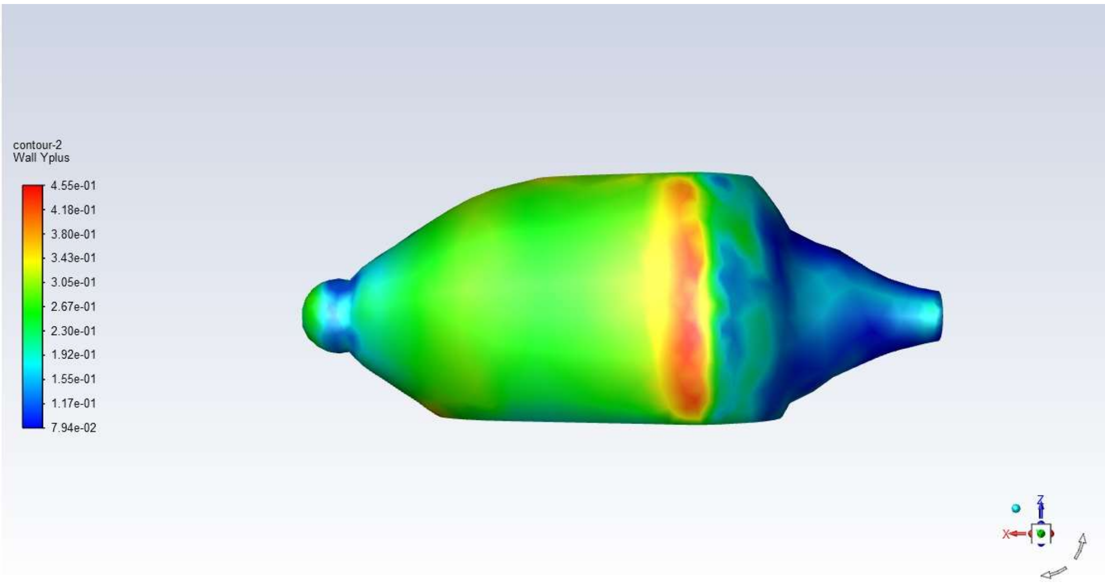

Figure 4.4 : Wall y+ Distribution over the Fuselage.

5. COMMENTS

Unmanned air vehicles are being more popular day by day. The usage of unmanned air vehicles is started with a hobby, but now the unmanned air vehicles are being used in many areas.

Unmanned helicopters can make a significant effect on forest fires. The first intervention is dropping fire extinguisher balls into the fire. This can help to decrease the spreading rate of the fire. In addition, the data collected and sent can play an important role in taking control of the fire.

The conceptual design study is followed by the mechanical design and CFD analysis. Calculations made again and again to obtain convergence between calculations and estimations. After the convergence is ensured, mechanical design is made using a CAD program. Then, using this 3D model, CFD analysis is done and the compability of the designed helicopter to the mission is seen.

As an engineer candidate, it is important to be able to both design, model and analyze a project.

REFERENCES

[1] Wildfires. (2020, July 10). Retrieved July 10, 2020, from https://earthdata.nasa.gov/learn/toolkits/wildfires

[2] Leishman, J. G. (2017). *Principles of Helicopter Aerodynamics*. Cambridge, United Kingdom: Cambridge University

[3] FT-200 FH Unmanned Aerial Vehicle (UAV). (n.d.). Retrieved July 10, 2020, from https://www.airforce-technology.com/projects/ft-200-fh-unmanned-aerial-vehicle-uav/

[4] Fire Scout VTUAV. (n.d.). Retrieved July 10, 2020, from https://www.naval-technology.com/projects/fire-scout-vtuav/

[5] Ziyan Blowfish Unmanned Helicopter System (UHS). (n.d.). Retrieved July 10, 2020, from https://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=2026

[6] VRT300. (n.d.). Retrieved July 10, 2020, from https://vrtech.aero/platforms/vrt300/

[7] Multi-function Unmanned Helicopter (Georgia). Retrieved July 10, 2020, from https://en.wikipedia.org/wiki/Multifunction_Unmanned_Helicopter_(Georgia)

[8] SKELDAR V-200. (n.d.). Retrieved July 10, 2020, from https://umsskeldar.aero/our-products/rpas-systems/v-200-skeldar/

[9] Precision Agriculture - RMAX. (n.d.). Retrieved July 10, 2020, from https://www.yamahamotorsports.com/motorsports/pages/precision-agriculture-rmax

[10] CAMCOPTER® S-100. Retrieved July 10, 2020, from https://schiebel.net/products/camcopter-s-100/

[11] Scout B1-100 UAV Helicopter. (n.d.). Retrieved July 10, 2020, from https://www.aeroscout.ch/index.php/scout-uav-helicopters/scout-b1-100- uav-helicopter

[12] Alpha UAV. (n.d.). Retrieved July 10, 2020, from https://alphaunmannedsystems.com/alpha-800-uav/

[13] Unmanned helicopter UVH R22 - UAVOS - Unmanned Systems Development, Research and Integration. (n.d.). Retrieved July 10, 2020, from https://www.uavos.com/products/vtols/unmanned-helicopter- uvh-r22

[14] Tanan 300 Unmanned Aerial System (UAS). (n.d.). Retrieved July 10, 2020, from https://www.naval-technology.com/projects/tanan-300-unmanned-aerial-system-uas/

[15] SKELDAR V-150. (n.d.). Retrieved July 10, 2020, from https://umsskeldar.aero/our-products/rpas-systems/v-150/

[16] Surveyor UVH – 290-E. (n.d.). Retrieved July 10, 2020, from http://www.bharatdronesystems.com/products/surveyor-uvh-290-e/

[17] UVH 25EL Helicopter -UAVOS -Unmanned Systems Development, Research and Integration. (n.d.). Retrieved July 10, 2020, from https://www.uavos.com/products/vtols/uvh-25el-helicopter

[18] Rotary-Bat (R-Bat) Unmanned Helicopter System. (n.d.). Retrieved July 10, 2020, from https://www.homelandsecurity-technology.com/projects/rotary-bat-r-bat-unmanned-helicopter-system/

[19] E950 - Industrial drone by Challis Helicopters Inc.: AeroExpo. (n.d.). Retrieved July 10, 2020, from https://www.aeroexpo.online/prod/challis-helicopters-inc/product-181419-19422.html

[20] FT-100 FH - Professional UAV by Flight Technologies: AeroExpo. (n.d.). Retrieved July 10, 2020, from https://www.aeroexpo.online/prod/flight-technologies/product-181379-36865.html

[21] VSR700. (n.d.). Retrieved July 10, 2020, from https://www.airbus.com/helicopters/UAS/VSR700.html

[22] Boeing A160 Hummingbird. (2019, December 14). Retrieved July 10, 2020, from https://en.wikipedia.org/wiki/Boeing_A160_Hummingbird

[23] Gyrodyne QH-50C Drone Anti-Submarine Helicopter (DASH). (n.d.). Retrieved July 10, 2020, from https://airandspace.si.edu/collection-objects/gyrodyne-qh-50c-drone-anti-submarine-helicopter-dash/nasm_A20090023000

[24] KAI / Boeing KUS-VJ Unmanned Attack Helicopter Gunship. (n.d.). Retrieved July 10, 2020, from https://www.militaryfactory.com/aircraft/detail.asp?aircraft_id=1661

[25] Rapier Unmanned Helicopter. (2019, November 29). Retrieved July 10, 2020, from https://en.wikipedia.org/wiki/Rapier_Unmanned_Helicopter

[26] AWHERO. (n.d.). Retrieved July 10, 2020, from https://www.leonardocompany.com/en/products/awhero

[27] MQ-8B Fire Scout: NAVAIR. (n.d.). Retrieved July 10, 2020, from https://www.navair.navy.mil/product/mq-8b

[28] SwissDrones. (n.d.). SwissDrones. Retrieved July 10, 2020, from https://www.swissdrones.com/product

[29] QUADs vs. UAV Helicopters. (n.d.). Retrieved July 10, 2020, from https://velosuav.com/info/

[30] *AIAA Aerospace Design Engineers guide*. (1998). U.S.: American Institute of Aeronautics and Astronautics.

[31]