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A New Optimization Model for Rotary-Wing Air Vehicle Propeller Design

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Abstract: In this study, the propeller characteristics of the aircraft have been optimized in terms of stabilization and manoeuvrability and it has been aimed to find the ideal propeller dimensions for the aircraft. A mathematical modelling has been developed for optimization and four different objectives are simultaneously optimized in the model. The results have been compared with simulation, analysis and real results. Gams and MATLAB programs have been used for developed mathematical model and simulation algorithm, respectively, and ANSYS program has been also used for CFD analysis. It has been observed that CFD analysis and mathematical model results are parallel to each other. As a result of the analysis, thanks to the developed model, a 6.47% improvement has been achieved in efficiency compared to the existing propeller system. In addition, an improvement of 3.93 times in "thrust" and 3.86 times in "total lift force" has been provided. Finally, it has been reported that the total drag force has been successfully minimized.

Key words: Propeller design, aviation, optimization, simulation, aircrafts, CFD analysis.

Döner Kanatlı Hava Aracı Pervanesi Tasarımı için Yeni Bir Optimizasyon Modeli

Öz: Bu çalışmada, uçağın pervane karakteristikleri stabilizasyon ve manevra kabiliyeti açısından optimize edilmiş ve uçak için ideal pervane boyutlarının bulunması amaçlanmıştır. Optimizasyon için yeni bir matematiksel model geliştirilmiş ve modelde dört farklı hedef aynı anda optimize edilmiştir. Elde edilen sonuçlar simülasyon, analiz ve gerçek sonuçlar ile karşılaştırılmıştır. Geliştirilen matematiksel model ve simülasyon algoritması için sırasıyla Gams ve MATLAB programı kullanılmış, CFD analizi için de ANSYS programı kullanılmıştır. CFD analizi ve matematiksel model sonuçlarının birbirine paralel olduğu gözlemlenmiştir. Analiz sonucunda, geliştirilen model sayesinde mevcut pervane sistemine göre verimlilikte %6,47'lik bir iyileşme sağlanmıştır. Ayrıca "itme kuvvetinde" 3,93 kat, "toplam kaldırma kuvvetinde" ise 3,86 kat iyileşme sağlanmıştır. Son olarak toplam sürükleme kuvvetinin başarılı bir şekilde minimize edildiği tespit edilmiştir.

Anahtar kelimeler: Pervane tasarımı, havacılık, optimizasyon, simülasyon, uçaklar, CFD analizi

1. Introduction

Systems consisting of blades designed considering aerodynamic or hydrodynamic criteria on a rotating shaft and moving with pushing or pulling power are called propellers. Propellers are used extensively in many systems, especially in air, sea and land vehicles, wind turbines and air conditioning systems [1].

As the propellers spin, they provide reducing the static pressure by accelerating the air in front of the propellers and increasing the static pressure at the rear of the propellers thanks to pitch. As a result of this operating principle, the vehicle moves forward. While the propellers are turning, they accelerate the air in front of them thanks to their pitch, reducing the static pressure and increasing the static pressure at the rear of the propeller, thus enabling the vehicle to move forward [2].

Propellers, which have different features and blade numbers according to their areas of usage and the vehicles they are used, can rotate clockwise and counter-clockwise in the direction of their leading edges. In addition, due to the Bernoulli Principle, the pressure difference in the front and rear regions of the propeller can resist the drag force of the relevant vehicle and the number of propellers can be determined depending on this situation.

Systems Drone systems contain many components such as engine, body, camera, compass, GPS (Global Positioning System), ESC (Electronic Speed Controller), battery, cable and screws. The most important component is the propeller systems. The efficient movement of rotary-wing unmanned aerial vehicles in the air in the desired formation and direction is possible with a correct propeller design. Propeller systems also contain many parameters, variables and restrictions. Under these constraints, it is not possible to determine the ideal propeller dimensions among many alternatives without using any solution methodology.

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In the literature, there are many methods [3-5] for designing propeller systems and determining their parameters. Gaggero et al., have developed multi-objective numerical optimization approach for design of marine propellers of a high-speed craft [6]. Gur and Rosen, have used a multidisciplinary solution approach for optimal design of propeller system of ultralight aircraft [3]. Zhang et al., have recommended multidisciplinary design optimization of a quadrotor fixed-wing hybrid UAV. The optimization method has been evaluated to design electric propulsion system in terms of flight performance [7]. Zhao et al., have developed a novel airborne electric propulsion measure system for fixed-wing UAV. They have implemented an experimental study to predict the truth of flight test and wind tunnel [8]. Dundar et al., have also used a fixed-wing UAV in terms of power consumption and performance analyses for all flight scenarios. Vertical take-off and landing (VTOL) concept have modelled in Simulink to design multirotor and propeller system for the best endurance [4]. (Bayraktar and Güldaş have one an experimental study using simulation approach based on the statistical methods to determine thrust and torque coefficients of the quadrotors [9]. Foeth and Lafeber, have optimized the parameters related to propeller geometry using NSGA-II Algorithm [10]. Lee et al., have intended to increase of flight time of the fuel cell powered quadcopter UAV. For this purpose, they have used genetic algorithm for weight optimization [11]. Bacciaglia et al., have proposed a solution methodology to optimization of the pitch propeller on the small entertainment ship boats by using Particle Swarm Optimization which is a metaheuristic algorithm [1]. Podsedkowski et al., have realized experimental tests on the pitch propeller of UAV in terms of propulsion system [2]. Magnussen et al., have optimized and designed various features (propeller, motor, power etc.) of UAV that is a multicopter using mathematical modelling [12]. Onay et al., have carried out the design of the two different propellers and have tested by comparing these propellers with the different methods [13]. Sinibaldi and Marino, have done an experimental study on the propulsion system of the mini drones Furthermore, they have examined the different between acoustic signature which is optimized and conventional propellers which is driven by brushless electric motors [14]. Kuantama and Tarca have optimized the thrust system of the quadcopter with ducted-propeller using CFD (Computational Fluid Dynamics) method [15]. Larocca et al., have optimized in terms of topological of the drone propeller which is used on the thrust system of multirotor by commercial CFD code [16]. Mian et al., have simulated a space mapping surrogate modeling to optimization of the UAV propeller shape. The CFD analysis has also used for accuracy of the optimization [17]. Kapsalis et al., have also used CFD method for the optimization of a tactical, fixed-wing UAV. The paper has represented the UAV layout optimization in the early stages of preliminary design with realizing Analysis of Variance (ANOVA) [18]. Dahal et al., have designed the propeller by experimental analyses in line with the goal of optimal thrust for UAVs that can fly altitude range between 3,000 and 5,000m and have used the CFD method to determine the validity of these experimental results [19]. Delbecq et al., have suggested a generic and efficient sizing methodology for electric multirotor drones. They have also performed sizing optimization for different flight phases and payloads [20]. ElGhazali and Dol have done the experimental analyses using ANSYS Fluent 16.1related to the improvement of the propeller system of UAVs which is multirotor [5]. McKay et al., have experimentally examined contra-rotating propellers of the UAV with multi-rotor [21]. Yeong and Dol, 2016 have optimized the aerodynamic performance of micro-drone using Shear Stress Transport K-Omega (SST k-ω) turbulence model [22]. Andria et al., 2018 have modelled and produced the drone propeller and have compared them with other propellers in terms of thrust performance [23]. Iannace et al., have used an artificial neural network to determine faults (unbalanced blades) on drone propellers [24]. Dumitrache et al., have designed drone propellers using Blade Element Momentum Theory (BEMT) and have analysed performance characteristics of them [25]. Wang et al., have used a direct optimal control method for the battery package topology of the small electric UAV. This optimization method has been tested on a small blended wing-body electric aircraft [26].

Studies in the literature generally focus on a single purpose (maximization of thrust) [15,19,23,27]. However, propeller design is not a problem that needs to be addressed unilaterally. Multiple objectives affect the propeller design process. In this article, it is obtained multi-objective propeller design optimization problem and the aircraft propeller has been simultaneously optimized under four different purposes (maximum thrust, maximum efficiency, maximum total lift force and minimum total drag force) in line with specific technical specifications and constraints. The reasons for considering more than one objective are stated as follows.

Among these purposes considered in the article, "thrust" and "total lift force"; it occurs depending on the number of propeller blades, blade angle and engine speed. These parameters that affect "thrust" and "total lift force" need to be optimized. That's why high propeller angle both positively affects thrust force and increases the drag force. Since the torque created by the motor will increase the pitch when the propeller angle increases, the torque required for rotation will also increase. The increase in torque means that the engine power should remain. The propeller efficiency is also calculated by considering all these data. For that reason, while designing the propeller, it is necessary to meet many objectives simultaneously. A mathematical model based on Multi

Objective-Non-Linear Mixed Integer Programming (MO-NMLP) has been developed to solve the problem in the article. The effectiveness of the proposed solution method has been tested by comparing it with the Simulation Algorithm and the data of the drone propeller used in the market. ANSYS program has been also applied to test efficiency and accuracy of the optimization results.

The contribution of the article to the literature is in two ways. First of all, best knowledge, there is no study in which optimal propeller design has been made considering the stated purposes. As well as, unique solution approach developed for the problem has a generic and dynamic structure and it is discussed for the first time in the literature, as far as known. Due to its generic and dynamic nature, the proposed solution approach can be easily used in all aircraft with propeller systems.

The originality of the article has been analysed in detail with comparisons, taking into account the studies that are closely related to the subject in the literature, and it is shown in Table 1 below.

Table 1. Comparison of this article with studies in the literature.

	Article's Features		
	Vehicle taken into account	*Objectives taken into account*	*Solution Methodology*
This article	Aircraft propeller design.	Maximum thrust, maximum efficiency, maximum total lift force and minimum total drag force	MO-NMLP (Exact solution methodology that guarantees optimal)
Literature	**Article's Features**		
Author(s) Information	*Vehicle taken into account*	*Objectives taken into account*	*Solution Methodology*
[28]	Marine propeller design.	Highest efficiency, the largest thrust, and the smallest maximum stress	NSGA-II
[29]	Marine propeller design.	Maximizing efficiency and minimizing cavitation	Multi-Objective Particle Swarm Optimization
[30]	Ship propeller design.	Efficiency ratio and thrust coefficient	NSGA-II
[31]	Marine propeller design.	The maximization of the efficiency and the minimization of the maximum cavity	Interactive Genetic Algorithms
[32]	Propeller-driven airplane	The maximization the stability of the lateral–directional motion the maximization longitudinal trim condition	Genetic Algorithm
[33]	The Vahana A^3 tilt-wing aircraft	Minimum energy consumption Maximum thrust	Betz Optimum Theory Blade Element Momentum Theory
[34]	Ship propeller design.	Minimum cavitation, maximum efficiency	Genetic Algorithm
[35]	Aircraft propeller design.	Minimization mass and costs	Genetic Algorithm,NSGA-II

Based on Table 1, we can express the differences of our article from the studies in the literature as follows. First of all, our article differs from other studies in the literature in terms of the purposes considered. In this article, the objectives of "total drag force" and "total lift force" are considered, along with thrust and efficiency purposes. As far as is known, it is understood from the results in the table that there is no study that considers these four objectives simultaneously. The second difference is the solution methodology used. The mathematical model developed for the solution of the problem was used for the first time in the literature due to the purposes and constraints considered. In addition, when the results in Table 1 are examined, it is seen that the methods used in other studies are based on metaheuristic algorithms and cannot guarantee the optimal. The method proposed in this article guarantees the optimal. For these reasons, it is thought that the article contributes to the literature.

The importance of the article is explained as follows. In the present situation, it is determined from the information in the literature that rotary-wing aircraft are subject to many accidents on account of adverse weather conditions [35, 36]. The aircraft gets out of control and falls by losing altitude, since suddenly changing air currents reduce the total lift force of propellers. The optimal propeller design depending on engine power requirements will keep under control the aircraft by providing abrupt power increases in such situations. In this article, it can be prevented the aircraft accident due to existing propellers by performing design optimal propellers thanks to proposed solution approaches.

2. Definition of the Problem

There are many parameters, constraints and decision variables that affect the system in the optimization of the drone propeller. While some of these decision variables take discrete values within the specified value range, some can take continuous values. The non-linear structure of the propeller optimization and mixed type of the variables make the solution of the problem very difficult. In addition, the continuous variable structure means that the relevant variable can take an infinite number of values. It is very difficult and takes time to determine the value range that optimizes the system for different purposes from this infinite range of values and to guarantee the optimal without using operations research techniques. The criteria considered in optimizing the propeller design in this article are shown in the Fig. 1.

As indicated in Fig. 1, the first factor considered in propeller design is technical specifications. In this context, the first variable value to be determined is the number of blades (propellers). The thickness-tightness ratio of the material (material constant) is known as the stretch ratio that the total pulling force on the propeller will create on the blades. If the produced total thrust force causes stretch on the blades, these new angles will directly affect the propeller performance. For this reason, if the required thrust force is higher than the desired elasticity coefficient of the propeller material, the propeller can be designed by increasing the number of blades and decreasing the force per blade.

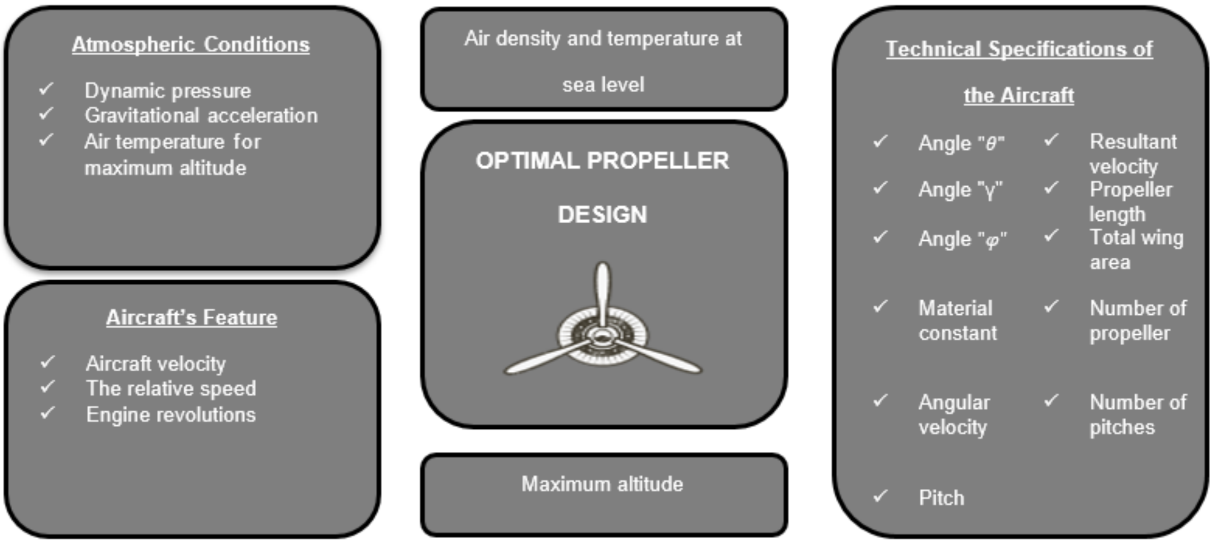


Figure 1. Factors affecting propeller design.

Blade (propeller) length, number of blades and pitch angle are three other technical factors affecting the design process. The number of blades is selected depending on the maximum pulling force needed according to the engine power and aircraft take-off weight. If the force on a knife is outside the strength limits according to the selected knife material, the number of knives is increased. Increasing the number of blades reduces thrust efficiency as it reduces the distance required to escape eddy currents. Because more induced drag force is created.

The angle between the zero support line and the propeller rotation plane of a section at a distance (r) from the axis of the propeller geometrically represents the propeller pitch. Generally, the geometric pitch varies along the blade of the propeller. For this reason, the geometric pitch of the section at a distance of 70% of the radius from the propeller axis is called the "average geometric pitch" of the propeller. The geometric pitch is a size dependent only on the geometry of the blades and is independent of the flight conditions.

The technical parameters that should be calculated in the propeller design and affect the performance of the system is the propeller angles. There are three different angles in the propellers: pfi(φ), theta(θ) and gamma(γ). The angle pfi(φ) represents the angle between the resultant velocity vector and the propeller plane. Theta(θ) represents the position angle of the local geometric pitch. Gamma(γ) represents that the angle between the lift force and drag force ratio vector with the resultant force. The combination of these angles has a huge impact on propeller performance.

The last technical parameters are resultant velocity, angular velocity and total wing area. The resultant velocity expresses the resultant velocity ($r\Omega(1\text{-}b)$ acting on the blade element in the propeller plane and the velocity of the current passing the propeller plane($U\infty(1+a)$). Angular velocity is the amount of angular displacement per second of the propeller depending on the engine speed. The total wing area is the area of the circle, which is the projection of the cross-section point taken at a distance of 70% from the root to the tip of the blade.

Two other important factors to consider in propeller design are “air density and temperature at sea level” and “maximum altitude”. The variation of the thrust and moment gradients of the propeller along the blade can be found by the equations given depending on the density of the air at the altitude where the propeller will operate. It is also possible to calculate the total thrust and torque acting on the propeller with the help of these data. Aerodynamically, the density of air is known as one of the direct parameters affecting flight.

Since atmospheric conditions are very effective in the formation of aerodynamic forces, they directly affect flight performance. Increasing altitude from sea level (sea level conditions accepted by ICEAO) changes the density, temperature, viscosity and pressure of the air. As a result of this situation, the performance of the aircraft changes depending on the altitude. Performance calculations were made using the formulas derived for the troposphere layer because rotary wing aircraft generally fly in the troposphere layer of the atmosphere.

Rotary-wing aircraft are considered for optimal propeller design in this article. There are basically two main expectations from rotary-wing aircraft: stabilization and speed. Among the advantages of rotary-wing aircraft compared to fixed-wing aircraft, the ability to take off-landing vertically and stay in the air can be mentioned first. The component that gives this ability is the propellers. The total take-off weight of the aircraft determines the characteristics of the propeller to be selected. The vehicle propulsion system is selected according to the selected propeller. Thus, the dynamics of the aircraft are determined approximately. For this reason, it is very important to choose the ideal propeller and propulsion system according to the desired characteristics of the aircraft.

3. Solution Methodology

In this paper, a mathematical model based on Multi-Purpose - Nonlinear Mixed Integer Programming has been developed and Simulation Algorithm has been used to solve the problem in Chapter 2. Information on the relevant methods is given below.

3.1. Mathematical Modelling

The mathematical model developed for the article is the Multi Objective-Non-Linear Mixed Integer Programming (MO-NMLP). A standard MO-NMLP consists of two parts, the objective and the constraints, as indicated in the equation below [28].

Objectives

$$max/\min Z = f_1(x,y) + f_2(x,y) + \ldots + f_n(x,y) \quad (1)$$

Constraints

$$g(x,y) = 0 \qquad : g(x,y) = a * x + b * y = 0 \quad (2)$$

$$h(x,y) \geq 0 \qquad : h(x,y) = c * x * y \geq 0 \quad (3)$$

$$x \in R^n \quad (4)$$

$$y \in \{0,1,2,\ldots,m\} \quad (5)$$

The $max/\min Z$ function equation 1 represents the problem's objective function or performance criterion in the model. “x” and “y” are decision variables that are unknown in the problem and must be found in line with the determined purpose and constraints. “a, b and c” represent the parameter values in the problem. It is seen that equation 2 is a linear function since the decision variables are not in the case of multiplication. However, in equation 3, the constraint has a nonlinear structure since the decision variables are multiplications. Finally, equation 4 and 5 in the model represent the types of decision variables “x” and “y” and the range of values they can take. Equation 4 shows that the variable “x” is in the set of real numbers and can take positive/negative/decimal/rational and irrational values. Equation 5 shows that the variables can only take 0 or positive integer values.

The solution architecture developed for the problem in line with the above information is shown in Fig. 2. Information on the optimization model developed to solve the problem stated in this article is given in the tables below. The parameters and variables considered in the problem are shown in Table 2.

As a result of the simulation tests performed in this article, “$cof_1 = 1000$”, “$cof_2 = 1$”, “$cof_3 = 1$” and “$cof_4 = 1$” were determined. In addition, in equation 36, the model was forced to have the system efficiency of 89% and above, thus, it was aimed to obtain the maximum efficiency from the system.

Table 2. Parameters and variables considered in the problem.

Parameters considered in the optimization model.	
g	acceleration of gravity
c_{max}	maximum value of material constant
c_{min}	minimum value of material constant
π	pi number
n_{max}	maximum value of engine revolutions
n_{min}	minimum value of engine revolutions
ro_{sfr}	density of air at sea level
T_{sfr}	temperature of air at sea level
v	aircraft speed
λ	constant coefficient
$altitude$	maximum altitude the aircraft can reach
a_{max}	maximum value of "a"
a_{min}	minimum value of "a"
b_{max}	maximum value of "b"
b_{min}	minimum value of "b"
bl_{min}	mimimum propeller lenght
bl_{max}	maximum propeller lenght
nb_{min}	minimum number of propellers
nb_{max}	maximum number of propellers
rs_{min}	the lower limit of the relative speed
rs_{max}	the upper limit of the relative speed
θ_{max}	maximum value of angle "θ"
θ_{min}	minimum value of angle "θ"
γ_{max}	maximum value of angle "γ"
γ_{min}	minimum value of angle "γ"
φ_{max}	maximum value of angle "φ"
φ_{min}	minimum value of angle "φ"
cof_1	Coefficient of objective 1
cof_2	Coefficient of objective 2
cof_3	Coefficient of objective 3
cof_4	Coefficient of objective 4
Positive continuous variables in the optimization model.	
r	70% of the blade length
$pfi(\varphi)$	Angle between resultant velocity and propeller plane
$sigma(\sigma)$	stiffness ratio of blade element
cd	drag coefficient
cl	lift coefficient
$theta(\theta)$	Seating angle of the propeller profile to the propeller hub at the blade root
bl	blade length
h	pitch
$gamma(\gamma)$	the angle between the lift force vector and the resultant force vector
q	dynamic pressure
s	total wing areas
ro	density of air
T	temperature of the air at altitude
ohm	angular velocity of the propeller
ur	resultant speed
mom	momentum
rs	relative speed
$thrust$	thrust
nu	efficiency
tlf	total lift force
tdf	total drag force
sp	shaft power
pl	propeller length
a	propeller exit plane induced speed
b	propeller current plane induced speed
c	material constant
n	engine revolutions
Positive integer variable in the mathematical model	
nb	number of propellers

The mathematical model developed for the problem is shown in Table 3.

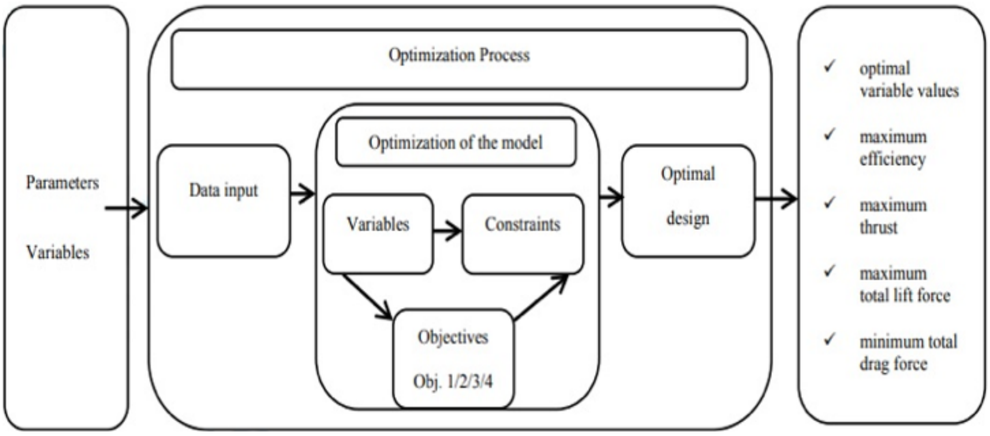


Figure 2. Optimal propeller design process.

Table 3. The objective functions and constraints in the mathematical model.

$makZ = cof_1 * nu + cof_2 * thrust + cof_3 * tlf - cof_4 * tdf$			(6)
$nb \leq nb_{max}$	(7)	$\pi * r^2 = s$	(23)
$nb \geq nb_{min}$	(8)	$2 * \pi * n = ohm$	(24)
$bl \geq bl_{max}$	(9)	$rs * (1 + a) - (1 - b) * (2 * \pi * r * n) * \tan(\varphi)=0$	(25)
$bl \leq bl_{min}$	(10)	$rs \geq rs_{min}$	(26)
$r = bl * 0.7$	(11)	$rs \leq rs_{max}$	(27)
$\theta \geq \theta_{min}$	(12)	$\gamma \leq \varphi$	(28)
$\theta \leq \theta_{max}$	(13)	$rs * (1 + a) = ur * \sin(\varphi)$	(29)
$2 * \pi * r * tan(\theta) = h$	(14)	$(1 - b) * \tan(\varphi) - \boldsymbol{nu} * 2 * (1 + a) * \tan(\gamma + \varphi) = 0$	(30)
$\sigma * 2 * \pi * r = nb * c$	(15)	$\pi * r * \sigma * ro * ur^2 * cl * \cos(fi + \gamma) = \boldsymbol{thrust}$	(31)
$\gamma \geq \gamma_{min}$	(16)	$\frac{1}{2} * cl * ur^2 * nb * r * c = \boldsymbol{tlf}$	(32)
$\gamma \leq \gamma_{max}$	(17)	$\frac{1}{2} * cd * ur^2 * nb * r * c = \boldsymbol{tdf}$	(33)
$cl * \tan(\gamma) = cd$	(18)	$thrust * r = mom$	(34)
$2 * b * \sin(2 * \varphi) - cl * (1 - b) * \sigma * \sin(\varphi + \gamma) = 0$	(19)	$2 * \pi * n * mom = sp$	(35)
$\frac{1}{2} * ro * v^2 = q$	(20)	$nu \geq 0.89$	(36)
$ro_{sfr} * \left(\frac{T}{T_{sfr}}\right)^{4.259} = ro$	(21)		
$T_{sfr} - \lambda * altitude = T$	(22)		

This optimization model, in equation 6, the objective function of the problem is stated. In this equation, there are four different objectives, three of these objectives are tried to be maximized (efficiency, thrust, tlf) while one of them (tdf) is tried to be minimized. "cof_1", "cof_2", "cof_3" and "cof_4" indicate the balance coefficient of each objective. As a result of the simulation tests performed in this article, "$cof_1 = 1000$", "$cof_2 = 1$", "$cof_3 = 1$" and "$cof_4 = 1$" were determined. In equation 7 and 8, the maximum and minimum integer values that the number of blades can take are expressed, and in equation 9 and equation 10, the maximum and minimum possible lengths of the blade length are specified. In equation 11, the "r" value associated with other formulations is calculated. In equation 12 and 13, lower and upper limits are given for "θ" angle, and in equation 14, "θ" angle is tried to be found for these purposes. In equation 15, the relationships between the number of blades, the material constant, the "r" value and sigma are expressed. In equation 16 and 17, the maximum and minimum values that the gamma variable can take are expressed. In equation 18 and 19, the formulation for the calculation of the variables "cl" and "cd" is indicated. In equation 20, 21, 22 and 23, dynamic pressure (q), total blade areas (q) and ideal air temperature and density at which the propeller will operate at optimal performance are calculated according to the density and temperature of the air at sea level. The omega value was found in equation 24, and the "pfi" angle was determined depending on the relative velocity in equation 25, 26 and 27. In equation 28, the superiority between the fi angle and the gamma angle is expressed, and the "ur" value is calculated in equation 29. In equation 30, the formulation related to efficiency, which is one of our goal variables, is expressed, and in equation 31, the formulas for the calculation of thrust are specified. The formulations for calculating “tlf” in equation 32 and “tdf” in equation 33 are given. In equation 34 and 35, formulations for determining “shaft power” are shown. In equation 36, the model was forced to have the system efficiency of 89% and above, thus, it was aimed to obtain the maximum efficiency from the system.

3.2. Simulation

Simulation is algorithmic technologies based on statistical foundations that enable the features of systems that cannot be studied, which in case of study bring high costs and risks, or that require a large number of trials, to be studied and tested by transferring them to the computer environment. In the simulation algorithm, the system tries to reach the best values that fulfil the objectives related to the numbers produced according to the uniform distribution within the value range that the relevant variables can take, but the optimal result cannot be guaranteed.

However, this method is used extensively by researchers because it produces suitable solutions for related problems in short solution times. In this study, it has been aimed to simulate the system before the design of the propeller, compare it with the data found for optimization and measure the performance of the system. The simulation study has been carried out using Matlab Simulink software.

The inputs determined for the simulation are “φ” and “γ” angle, blade length, number of blades, “a” and “b” lengths, “c” material constant, “n” engine revolutions, relative and vehicle speed. Thrust, efficiency, total lift force (tlf) and total drag force (tdf) has been calculated as outputs. In the next section, application study will be carried out in line with the defined solution methodologies.

4. Application Study

4.1. Optimization of the Drone System

Application studies have been carried out using Gams Optimization Program and Matlab Simulink program on computers with 16 GB RAM and 3.2 Ghz processor. The features of the “alpha mini drone” have taken into account in the application study and these features are given in Table 4. In this table, in addition to the existing (alpha mini drone) drone information, the value ranges of the variables to be considered in the optimization study are also expressed.

In the direction of parameters in Table 4, the mathematical model, simulation and real data values have been compared in terms of four different objectives. Analysis results and variables values have been shown in Table 5 and Table 6, respectively.

Table 4. Data used in application study.

Symbol	Unit	Real Parameters	Optimization Parameters	Symbol	Unit	Real Parameters	Optimization Parameters
g	m/s^2	9.81	9.81	b_{max}	-------	0.02	0.05
c_{max}	-------	0.16	0.30	b_{min}	-------	0.02	0.01
c_{min}	-------	0.16	0.15	$plmin$	m	0.127	0.762
π	-------	3.14	3.14	$plmax$	m	0.127	0.127
n_{max}	rad/s	282.6	1046.67	$nbmin$	-------	2	6
n_{min}	rad/s	282.6	104.667	$nbmax$	-------	2	2
$rosfr$	kg/m^3	1.225	1.2256	$rsmax$	m/s	8	20
$Tsfr$	^0K	288	288	$rsmin$	m/s	8	8
v_{max}	m/s	8	20	θ_{max}	degree	25.2	37
v_{min}	m/s	8	3	θ_{min}	degree	25.2	20
λ	-------	0.0065	0.0065	γ_{max}	degree	0.01	5
$altitude$	m	3000	3000	γ_{min}	degree	0.01	0.01
a_{max}	-------	0.16	0.8	φ_{max}	degree	20.63	35
a_{min}	-------	0.16	0.1	φ_{min}	degree	20.63	18

When the results in the Table 5 are examined, it is understood that four different objectives have been optimized simultaneously with mathematical modelling and the best result that could be reached under the relevant constraints has been achieved.

Table 5. The best values obtained for each method as a result of the application.

Objective	Existing values	Simulation(Mean)	Mathematical Model
Efficiency	0.8444	0.61066	0.899
Thrust	12.5963	49.9264	49.499
Total lift force	1.3160	5.25022	5.086
Total drag force	0.0002295	0.327	0.000887

Table 6. The values of variables according to analysis results.

Variables	Existing values	Simulation	Optimization
number of propellers (nb)	2	4	2
propeller length (pl)	0.127	0.101584	0.127
engine revolutions (n)	45	96.589167	122.634
material constant (c)	0.16	0.227	0.225
theta(θ)	25.20	28.5	30.894
fpi(φ)	20.63	26.35	18
gamma(γ)	0.01	2.3001	0.01
a	0.16	0.479	0.1
b	0.02	0.03175	0.011
rs (relative speed)	8	13.48	20
v (aircraft speed)	8	13.6	16.624

Table 7. The values of variables according to analysis results.

Objective	Efficiency	Thrust	Tlf	Tdf
The best solution from Efficiency	0.8999	6,186	0.5228	0.00000913
The best solution from Thrust	0.4119	408.2	44.04	3.853
The best solution from Tlf	0.4119	408.2	44.04	3.853
The best solution from Tdf	0.8999	6,186	0.5228	0.00000913

In the Table 5, the average values related to simulation studies have been given. The random numbers have been generated according to normal distribution for the simulation algorithm and the algorithm has been run 1000 times. The detailed analysis of simulation results for each objective has been given in the Table 7.

When Table 6 is examined, it has been determined that while a objective is achieved, very bad results are obtained from other objectives, and it is understood that the simulation method cannot simultaneously optimize the goals. In addition, the normalized percentage graph of the results in Table 6 is shown in Fig. 3.

It can be seen from the Fig. 3 that the parameters affecting the “efficiency maximization” and “tdf” minimization have a linear relationship with each other. In addition, it has been determined that there is a positive relationship between the parameters optimizing “thrust” maximization and “tlf” maximization. As a result, it is understood that “efficiency” and “tdf” have a negative correlation with other purposes.

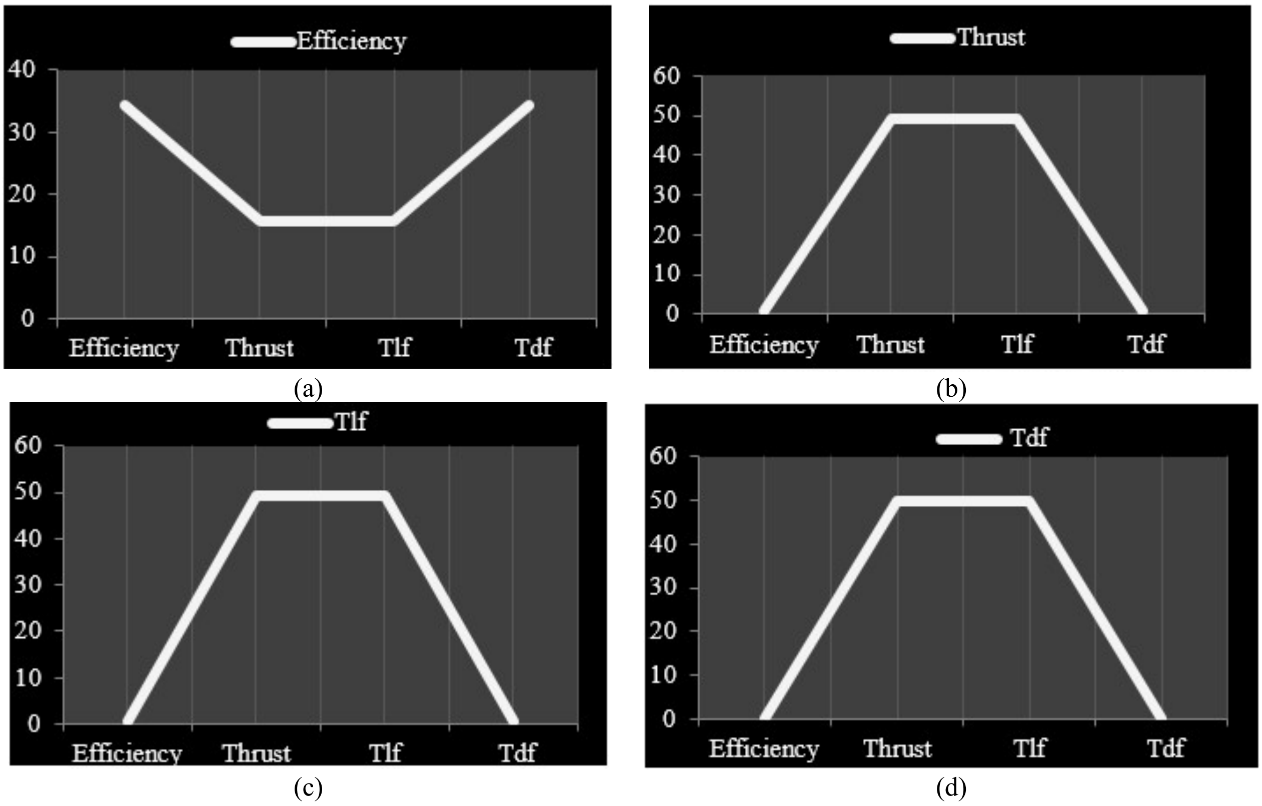


Figure 3. Normalized percentage graph of objective function values. a) Considering only the efficiency objective from the objective function b) Considering only the trust objective from the objective function c) Considering only the tlf objective from the objective function d) Considering only the tdf objective from the objective function

4.2. Analysis of the Simulation Result

In this section, the effects of "pfi", gamma and blade length variables on the propeller design are analyzed in detail based on the simulation results, keeping other parameter values constant, and summarized in the figures below. It is observed that as the "gamma angle" increases, the "tdf" objective increases exponentially to a large extent in Fig. 4. In addition to this, it is seen that "efficiency", "thrust" and "tlf" decrease, although the rate of change is small. It has been stated that the value which maximizes "efficiency", "thrust" and "tdf" and minimizes "tdf" is optimal value.

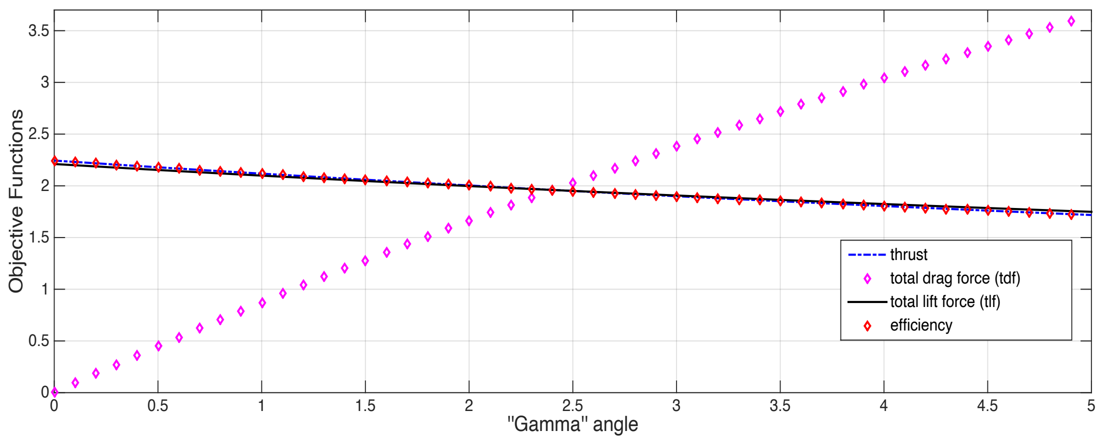


Figure 4. Effect of gamma angle changes on objective functions.

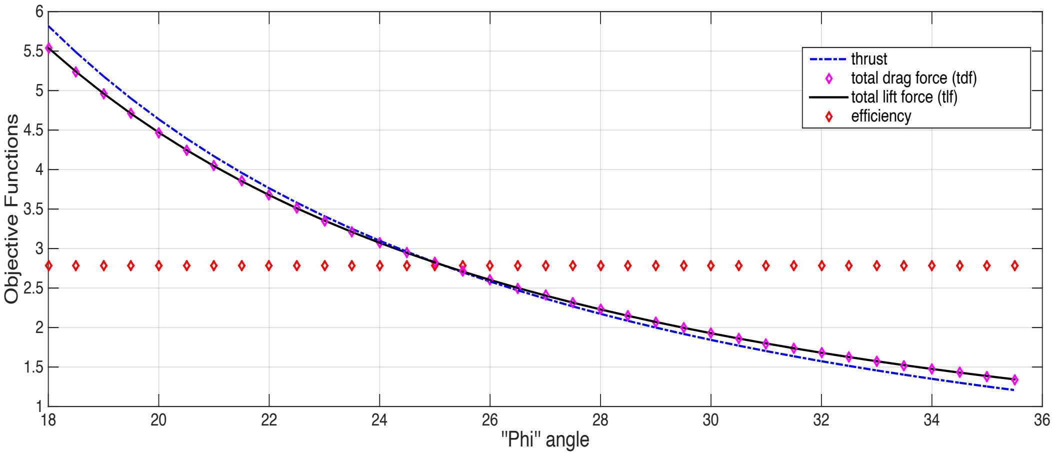


Figure 5. Effect of pfi angle changes on objective functions.

In the Fig. 5, it is understood that as the "pfi" angle increases, the objectives of "thrust", "tlf" and "tdf" decrease significantly, while the aim of "efficiency" remains stable in general. The Fig. 6 shows the effect of change in blade length on objective function values. Accordingly, it is understood that the change in blade length has little effect on "efficiency" and significantly changes other purposes.

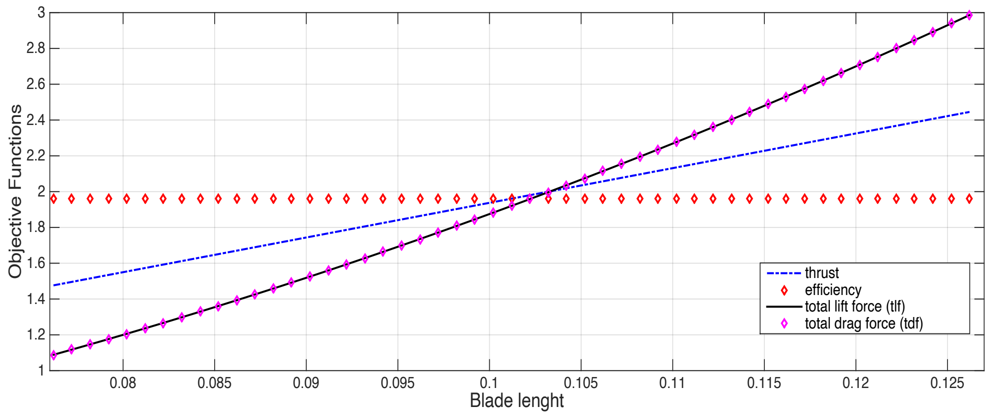


Figure 6. Effect of blade length changes on objective functions.

In the Fig. 5, it is understood that as the "pfi" angle increases, the objectives of "thrust", "tlf" and "tdf" decrease significantly, while the aim of "efficiency" remains stable in general. The Fig. 6 shows the effect of change in blade length on objective function values. Accordingly, it is understood that the change in blade length has little effect on "efficiency" and significantly changes other purposes.

4.3. ANSYS Analysis of the Optimization and Existing Values System

In this article, it has been done CFD analysis for the purpose of verification values obtained as a result of optimization and the analysis results have been compared with the existing propeller values. ANSYS SpaceClaim Program has been used in order to propeller design. It is known that the blade, which starts from the center of the propeller and is designed with a length of 127 mm, should be thicker in the root part and thinner towards the tip depending on the twister angle. A combination of four different NACA profiles has been designed in the 5 different points starting from the zero point of the blade length (40%, 50%, 60%, %70 and %100 points of the blade). The used NACA profiles are shown in Fig. 7.

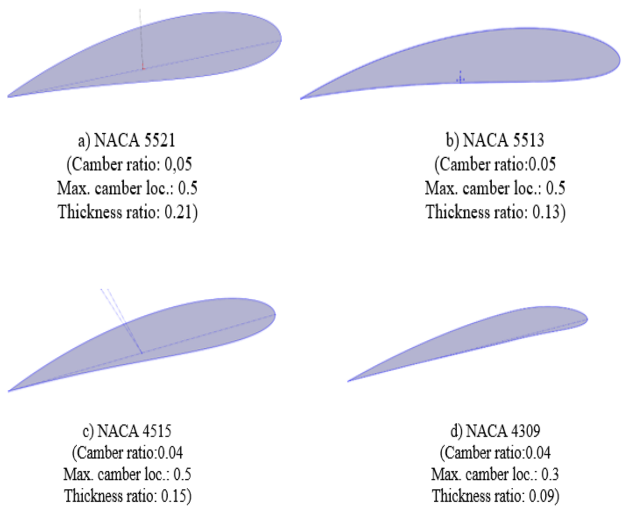


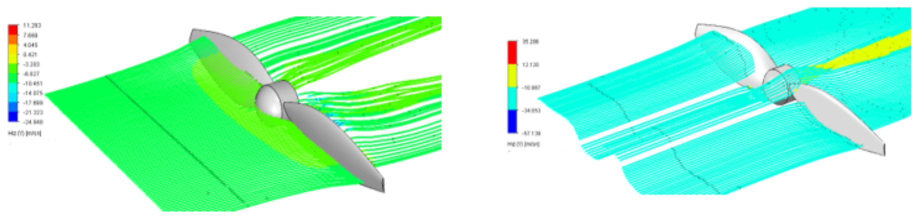
Figure 7. The NACA profiles used for the blade design.

The pitch root angle and wing tip angle have been determined as 25.2 and 10 degrees for the design made taking into account the number of turns of the propeller, the velocity of the fluid entering the propeller, the pitch angle of the propeller in line with the propeller information used in the drone market in real conditions. In the optimal results obtained with the mathematical model, the propeller root angle has been determined as 30,894 degrees and the blade tip angle has been determined as 14 degrees. The current propeller and optimal propeller designs are shown in Fig. 8.

Figure 8. Blade designs of the propeller

"CFD analysis of the related design", "the pressure values at the 0.7r point referenced for the mathematical model", and "the relations between existing constraints propeller and optimal constraint propeller according to the thrust force values" have been calculated as a percentage (%).

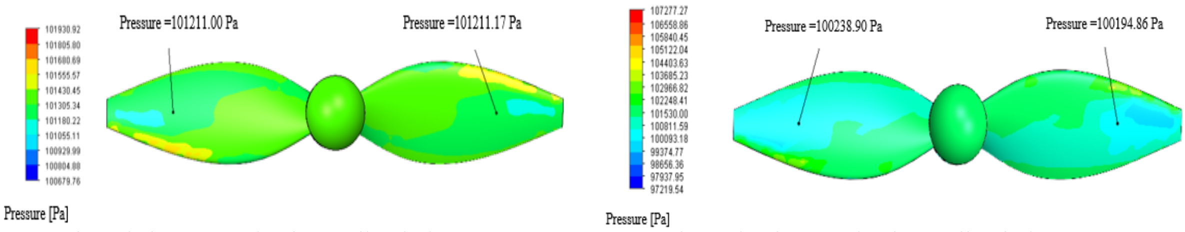
In the results of the analysis made in the real constrained propeller design, the flow lines have been formed properly and maximum flow velocity of 11.293 m/sec has been observed at 2700 rpm propeller speed. In the optimal constrained design, a maximum flow velocity of 35.206 m/sec have been found at 7358 rpm. The flow lines have been given in Fig. 9.



a. Existing constrained propeller design. **b.** Optimal constrained propeller design.

Figure 9. CFD flow velocity profiles.

The difference between the pressure passing under the wing profiles of the propeller blades and the pressure passing over the profile is the main parameter that creates the bearing force of the propeller. The maximum and minimum pressures occurring at 0.7r distance of the blade in both real constrained and optimal constrained propeller designs are shown in Fig. 10.



a. The existing constrained propeller design pressure results.

b. The optimal constrained propeller design pressure results.

Figure 10. Optimal and current propeller design comparison.

5. Conclusion

In this paper, the design of the drone propeller systems has been tried to be optimized with a new mathematical modelling used for the first time in the literature. An application study based on real data has been conducted to test the effectiveness of the proposed models. The propeller structure of the alpha mini drone has been considered for the application study. First of all, the optimization process has been carried out using the mathematical modelling method in line with the relevant propeller data. Then, the data obtained as a result of the optimization have been compared with the existing propeller values and simulation results. In consequence of the comparison study, it has been determined that the optimal propeller dimensions have been obtained with the mathematical modelling method and four different objectives have been optimized simultaneously. In addition, according to the analysis study, it has been determined that the simulation algorithm could not optimize the objectives simultaneously. The simulation algorithm found good results for purposes "thrust" and "tlf", while bad results for purposes "efficiency" and "tdf". Comparing the mathematical modelling results with the existing propeller values, it has been determined that quite superior results have been obtained for the purposes of "efficiency", "tlf" and "tdf". Moreover, CFD analysis has been performed using ANSYS program to test the success of optimization results on the real system data. It has been observed that CFD analysis and mathematical model results are parallel to each other.

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