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Research Article

Multidisciplinary Conceptual Design Methodology and Design Tool for Rotor Blades of Advanced Helicopters

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Abstract

A multidisciplinary rotor blade design approach, which is suitable for conceptual design, sizing and evaluation of helicopters is presented. Blade outer surface and structural geometry is represented by a geometrical model in which chord, thickness ratio, camber ratio and twist distributions along the blade radial stations can be defined as linear or nonlinear functions. Distribution of the number of laminas for both skin and spar were also defined in the presented model parametrically. Low level fidelity analysis methods were chosen to reduce the computing time. Performance analysis and sizing of the vehicle are performed by an in-house developed code named as ROTAP based on BEMT. Airfoil aerodynamic characteristics are calculated by Xfoil, a well-known panel method software. Structural analyses are performed by 1D finite element method approach. Cross-sectional properties of the composite beam are calculated by VABS software and displacements under the loads are calculated by the GEBT. All these programs are modified and embedded into the developed code and a single program with user friendly interface emerged. Developed algorithm and tool can be used for performance and structural strength calculations during the rotor design optimization studies at the conceptual design stage.

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Gelişmiş Helikopter Rotor Palaları İçin Çok Disiplinli Kavramsal Tasarım Metodu ve Tasarım Aracı

Makale Bilgisi

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Anahtar Kelimeler: Rotor Palası, Kavramsal Tasarım Eniyilemesi, Performans, Yapısal Dayanım.

Öz

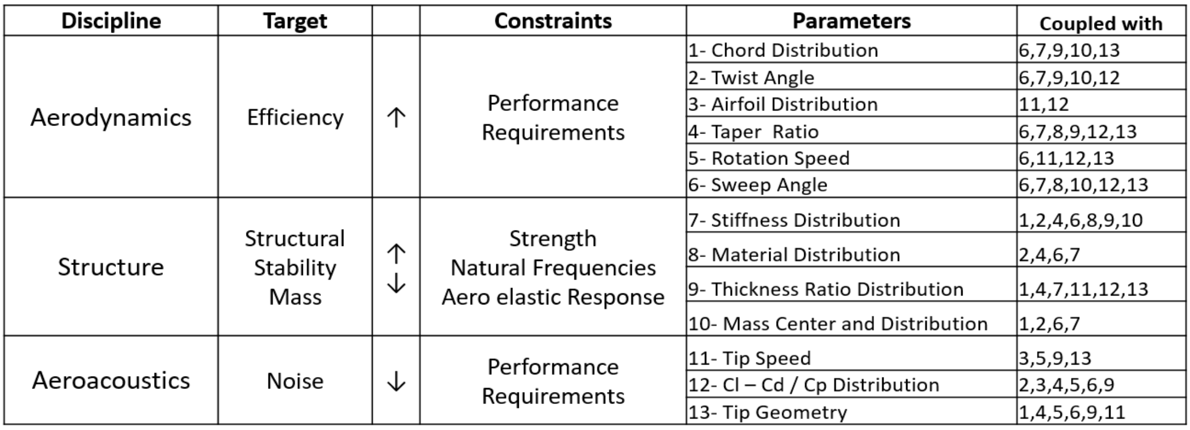
Bu çalışmada, helikopter kavramsal tasarım, boyutlandırma ve değerlendirme aşamalarında kullanıma uygun, çok disiplinli rotor palası tasarım yaklaşımı anlatılmıştır. Pala boyunca lineer ve non-lineer dağılım fonksiyonları olarak tarif edilmiş veter, kalınlık oranı, kamburluk oranı, ve burulma parametreleri ile pala dış yüzeyi ve yapısal geometri temsil edilmektedir. Kaplama ve spar için katman sayılarının dağılımı da çalışmada izah edilen modelde gösterilmiştir. Düşük seviyede fakat yeter çözünürlükte analiz methodları seçilerek toplam çözüm süresi azaltılmıştır. ROTAP adlı, BEMT metdou ile çalışan ve yazar tarafınfa geliştirilmiş helikopter boyutlandırma kodu, performans analizleri ve boyutlandırmada kullanılmıştır. Airfoillerin aerodinamik karakteristikleri ise, literatürde iyi bilinen bir panel kodu olan Xfoil yardımıyla hesaplanmıştır. Yapısal analizlerde bir boyutlu sonlu elemanlar yaklaşımı kullanılmışıtır. Kiriş kesit özellikleri VABS, yükler altında ki deplasmanlar ise GEBT yardımı ile hesaplanmıştır. Tüm bu yazılımlar modifiye edilerek geliştirilen algoritma içerisine gömülerek kullanıcı dostu bir arayüzü olan tek bir kod altında birleştirilmiştir. Geliştirilen algoritma ve tasarım aracı, rotor tasarımı kavramsal tasarım aşamasında palanın performans ve yapısal dayanım analizlerinde kullanılabilir.

1. INTRODUCTION

Helicopters are complicated air vehicles compared to the fixed wing aerial vehicles where lift, thrust and control are performed by a single component named as the rotor that is the source of the most important problems of design such as performance, vibration and noise. Therefore, rotor sizing can be represented as the core of whole vehicle design process. On the rotor design, there are many design targets for different disciplines that are influenced by different rotor parameters. A simple classification of design targets, constraints and parameters are shown in Figure 1. Figure shows that, aerodynamic, structure and aeroacoustics characteristics of the blade are the functions of design parameters. However, many of these parameters have coupled effect with other parameters on the performance. For instance, chord distribution is effective on the aerodynamic characteristics of the blade, however it also effects the stiffness distribution and the tip geometry that are the parameters of structural strength and aeroacoustics respectively. The parameters for aerodynamics, structure and aeroacoustics disciplines and their coupled parameters are given in the Figure 1 by their parameter numbers. All these coupled effects clearly indicate that a multi-disciplinary design approach is necessary.

There is a wide variety of publications on multi-disciplinary design of helicopter rotor blades. These studies have focused on different disciplines and analysis techniques on different fidelity levels. Aerodynamic and performance design approaches have mostly focused on hover power minimization [1]. Airfoil shape and distribution on the blade are two of the most important parameters to increase the performance [2]. Blade planform [3] and airfoil shape can be considered together to decrease the hover power requirement [4]. Other rotor parameters such as twist and rotor diameter are also important for rotor performance improvements [5, 6]. Vibration is another constraint for the blades. Natural frequencies should be sufficiently far from excitation frequencies, [7]. Most of the modern helicopter blades are designed and manufactured based on composite materials. On the other hand, analysis and design of rotor blades consisting of composite materials are more difficult compared to isotropic metallic materials due to their discrete laminate structure and complicated failure criterions [8]. Aeroelastic response of the blades should also be considered on the rotor blade structural design [9]. Manufacturing constraints and cost predictions are the other disciplines, which should be taken into account on the helicopter rotor blade design [10].

Due to the large number of parameters driving the design study, fidelity of the analysis techniques defines the feasibility of the design methodology. Results should be sufficiently accurate and the solution time should be acceptable for industrial design methodologies [11]. Nevertheless, high accuracy requires high fidelity analysis techniques, which are poor on computation time [12]. So different fidelity level analysis techniques may be used depending on the goal of the study [13]. Multi fidelity methods are also used to decrease the solution time without any major loss on accuracy [14]. The present study describes the methodology of a multidisciplinary rotor blade design for the conceptual design stage of a helicopter development processes. In the present approach, performance, blade structural strength and some manufacturing constraints are considered. It is aimed to obtain a framework that is suitable for industrial applications by integration of some open source and in-house developed codes. Since conceptual design stages require evaluation of thousands of alternative design solutions, low level analysis techniques are preferred for calculations to decrease required solution times.



Discipline	Target		Constraints	Parameters	Coupled with
Aerodynamics	Efficiency	↑	Performance Requirements	1- Chord Distribution	6,7,9,10,13
				2- Twist Angle	6,7,9,10,12
				3- Airfoil Distribution	11,12
				4- Taper Ratio	6,7,8,9,12,13
				5- Rotation Speed	6,11,12,13
				6- Sweep Angle	6,7,8,10,12,13
Structure	Structural Stability Mass	↑ ↓	Strength Natural Frequencies Aero elastic Response	7- Stiffness Distribution	1,2,4,6,8,9,10
				8- Material Distribution	2,4,6,7
				9- Thickness Ratio Distribution	1,4,7,11,12,13
				10- Mass Center and Distribution	1,2,6,7
Aeroacoustics	Noise	↓	Performance Requirements	11- Tip Speed	3,5,9,13
				12- Cl – Cd / Cp Distribution	2,3,4,5,6,9
				13- Tip Geometry	1,4,5,6,9,11

Figure 1. Rotor parameters, influenced design targets and coupling.

Developed methodology consist of three main modules. The first one is the geometrical modelling that defines the blade geometry for given parameters. Second one is the performance analysis for the required flight conditions and the last one is the structural analysis module that obtains the structural strength of the blade under the aerodynamic loads calculated by the performance analysis module (Figure 2).

The geometrical modelling module allows either constant, linear or non-linear distribution of all blade parameters along the blade. Therefore, complicated blade geometries can be searched during the conceptual design exploration phase. Moreover, the methodology is suitable for multi-fidelity analysis.

The aim of current study is evaluation of performance and structural characteristics of a blade by a single design environment. For this purpose, a design tool is developed that can be used either for analysis of specific blade configurations or as a fully automated analysis module to be used in optimization algorithms. The developed algorithm and tool allows design of helicopter rotor blades and propellers that have complex blade surface geometry and detailed structural model with only a number of design parameters. Therefore, detailed design optimization even at the conceptual design stage can be possible.

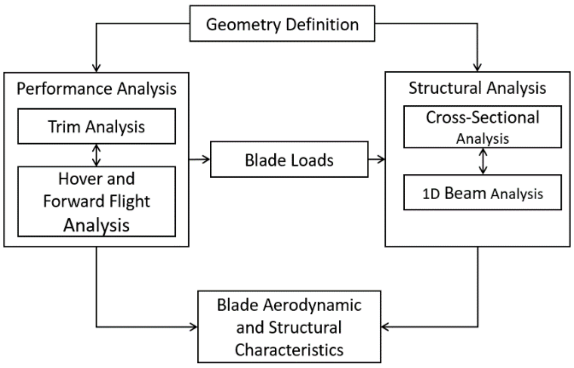


Figure 2. General Flow chart of the design process.

2. BLADE GEOMETRICAL DEFINITION

Airfoil geometry, chord distance, twist angle and sweep angle (generally at the tip) are the main parameters that define the blade geometry. These parameters may be chosen as constant along the blade for ease of manufacturing and cost reduction. However, this causes decrease in performance. Today's modern rotor blade usually have parameters that vary regionally along the blade to increase the performance [15]. Thicker airfoils have higher lift coefficients at lower speeds, however their drag divergence characteristics are poor at high tip speeds. Therefore, thicker airfoils are suitable for blade regions closer to root and thinner airfoils are suitable for tip regions. In addition, thick airfoils perform better at root sections due to their resistance to large bending moments. Twist angle and the taper ratio of the blade influence the efficiency of the rotor at different flight speeds. Angle of sweep at the tip of the blade reduces the tip Mach number and affects the noise level of the systems. Bagai defines blade geometry with blade parameters that vary regionally, to obtain optimal rotor blade according to design goal [16]. Modern airfoils are distributed along the blade according to their thickness ratio in Ref. [16]. Another study for blade shape optimization is done by Vu et al [4]. In this study, airfoil shape and planform of the rotor blade are optimized to reduce hover power requirement. Airfoil is defined by class function / shape function transformation method (CST) and planform for chord distance distribution is defined by root chord, chord taper starting point and taper ratio. In another study by Elfarra [3], chord distribution is defined with cubic splines and rotor blades with optimal performance are obtained.

Advanced helicopters require rotors that show superior aerodynamic and structural performance and they have complicated blade geometry in terms of manufacturing. In the present study, blade geometry is defined as continuous non-linear functions along the blade to optimize performance, strength and noise. Airfoil design and distribution of the airfoils along the blade and chord, twist angle and angle of sweep distributions are considered on the blade geometry definition.

Airfoil geometry are generally defined by functions such as spline functions [17], Class function / Shape function transformations (CST) [4] or PARSEC [18]. The main purpose of these methods are to reduce the number of parameters to optimize for every airfoil. If there is only one or just a few airfoils to optimize on the blade, then these methods are feasible. In the case where the airfoil geometry changes along the blade radial stations continuously, it is necessary to reduce the number of parameters. Airfoil families that are specifically developed for rotor systems such as Boeing VR-X airfoils for rotor blades [19] are available. Nevertheless, the present study focuses on conceptual design stage and NACA airfoils will be used for simplification of parametrization process. In NACA airfoil series, every digit of the airfoil defines a characteristics of the airfoil. As an example, first digit defines the maximum camber ratio as percentage, second digit defines the position of the maximum camber from the leading edge and last two digits define the maximum thickness ratio as percentage in the 4 digit airfoils [20]. NACA airfoils are very well known and studied airfoils. Even though they are old, they are suitable for conceptual design stages and they have many published test results of aerodynamic characteristics, which are the classics today [20, 21].

In the model, every airfoil is described by thickness ratio, camber ratio and the location of camber ratio from the leading edge of the airfoil. Therefore, there are only three parameters that define the airfoil. On the other hand, airfoils change from root to tip of the blade.

Thicker airfoils at the root and thinner airfoils at the tip are chosen to get better aerodynamic and structural performance. The airfoil parameters at any radial station of the blade are defined by the distribution functions (Figure 3).

These functions can be chosen as linear, polynomial, spline, power or of any other form. The type of the chosen function determines the number of parameters to be optimized. The selected thickness ratio distribution function along the blade is given in Eq. (1):

$$Th(r) = C_1(1 + C_2 r^{C_3}) \tag{1}$$

where C_1, C_2 and C_3 are the parameters to be optimized. In this function, C_1 describes the maximum value of the parameter on the distribution graph, C_2 describes the ratio of change from the maximum value at the root to the minimum value at the tip and C_3 can be defined as curve constant describing how the curve changes along the blade. Figure 4 shows exemplary cases for the thickness ratio distribution along the blade span for different parameters.

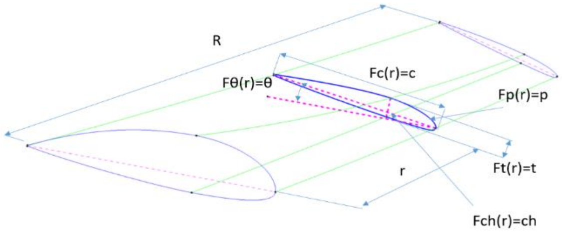


Figure 3. Blade definition by distribution functions.

Similar distribution functions can be created for other two airfoil parameters, i.e., camber ratio and location of the camber ratio. Not only airfoil but also the other blade parameters; chord distance distribution, twist angle distribution and angle of sweep distribution can be parametrized by these functions as well. However, more suitable functions should be selected according to the nature of parameters. Such as power functions are more suitable for angle of sweep distribution since its variation is expected at the tip of the blade rather than other blade span locations. Figure 5 shows chord distribution and angle of sweep distributions for alternative distribution functions for a helicopter rotor blade.

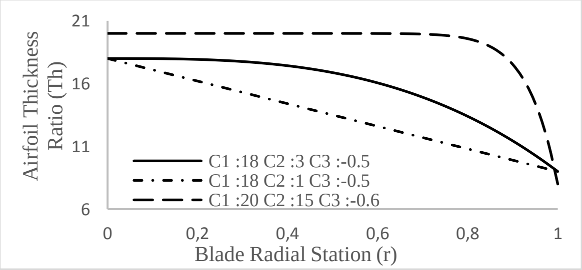


Figure 4. Thickness ratio distribution along the blade span for different distribution function constants.

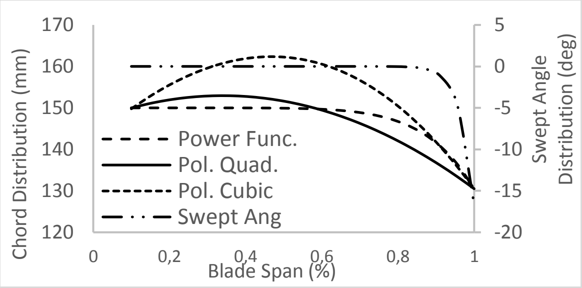


Figure 5. Chord distance and swept angle distributions along the blade span with alternative distribution functions.

It should be remembered that the type of distribution function defines the total number of parameters to be optimized. The total number of the parameters defines the total number of Design of Experiment (DOE) points with DOE description method and as a result, the total solution time. Table 1 shows the distribution functions and their parameters of a blade outer surface geometry in the case of all functions distributed by power functions or quadratic polynomial functions.

Table 1. Functions and the parameters which define the outer surface geometry of the blade.

F_1	F_2	F_3	F_4	F_5
Chord Dist.	Thickness Dist.	Camber Dist.	Twist Dist.	Swept Dist.
$C_{1,1}$	$C_{2,1}$	$C_{3,1}$	$C_{4,1}$	$C_{5,1}$
$C_{1.2}$	$C_{2,2}$	$C_{3,2}$	$C_{4,2}$	$C_{5,2}$
$C_{1,3}$	$C_{2,3}$	$C_{3,3}$	$C_{4,3}$	$C_{5,3}$

Rotor radius and blade root cut-out are the other parameters to define the total blade geometry. By assigning values to the function parameters, a sample blade geometry for the parameters given in the Table 2 is obtained as presented in Figure 6. A different blade geometry will be obtained by assigning different values to function parameters.

Table 2. Function values for sample blade geometry.

F_1	F_2	F_3	F_4	F_5
Chord Dist.	Thickness Dist.	Camber Dist.	Twist Dist.	Swept Dist.
150	20	6	10	1500
10	2	1	1	10
-0,6	-0,5	-0,5	-1	-0,05

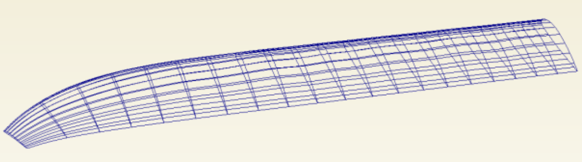


Figure 6. A sample blade geometry obtained by distribution functions.

3. PERFORMANCE ANALYSIS

Rotorcraft Design Program (*Rotorlu Hava Araçları Tasarım Programı* - ROTAP) is a conventional helicopter sizing tool developed at Istanbul Technical University [22]. Aerodynamic analysis module of the ROTAP is modified and embedded inside the current study. ROTAP uses Blade Element Momentum Theory (BEMT) to calculate performance characteristics of the blade. According to this theory, blade is divided into finite number of elements and then, local velocities and forces are calculated and integrated over the blade radial direction (Figure 7 and Figure 8).

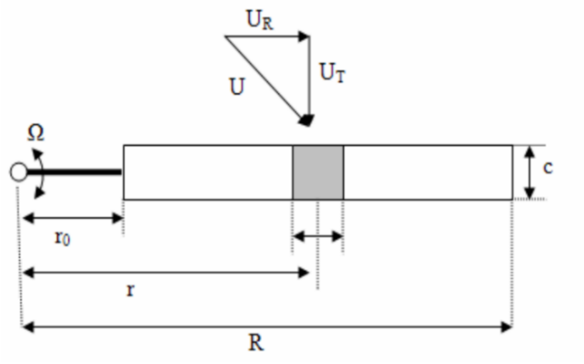


Figure 7. Blade Element Model.

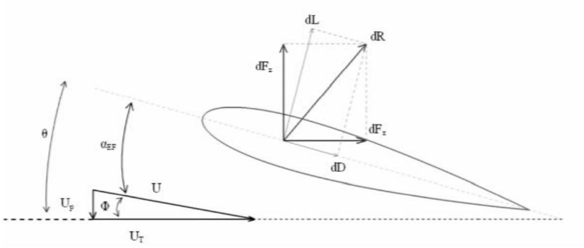


Figure 8. Local velocities and forces.

U_r, U_T, U_P and U are local velocities, θ is control collective angle, α_{ef} is effective angle of attack, dFx, dFz, dD, dL, dR are local forces, R is the rotor radius, r_0 is the root-cut, c is the chord, Ω is the rotational speed in rad/sec and r is the local position of blade element.

In addition, U_T is horizontal velocity of the air that depends on rotational speed and radial position of blade element ($U_T = \Omega r$) and U_P is inflow velocity calculated by momentum theory. Inflow ratio is the ratio of inflow velocity to the tip speed of the rotor blade and it can be calculated by Eq. (2) with the Prandtl's tip loss effect [23].

$$\lambda = \sqrt{\left(\frac{\sigma a}{16F} - \frac{\lambda_c}{2}\right)^2 + \frac{\sigma a}{8F}\theta\frac{r}{R}} - \left(\frac{\sigma a}{16F} - \frac{\lambda_c}{2}\right) = \frac{v_i + V_c}{\Omega R} = \frac{U_p}{\Omega R} \quad (2)$$

Where F is Prandtl's tip Loss Function, σ is solidity of the blade, a is lift curve slope of the airfoil, v_i is inflow velocity, V_c is climb speed, $\lambda_c = \frac{V_c}{\Omega R}$ and λ is total inflow ratio.

Total required power can be calculated by Equation (3)

$$C_P = C_Q = \frac{kC_T{}^2}{2\sqrt{\lambda^2 + \mu^2}} + \frac{\sigma C_{d0}}{8}(1 + K\mu^2) + \frac{1}{2}\left(\frac{f}{A}\right)\mu^3 + \lambda_c C_T \quad (3)$$

Induced power correlation factor k, is an empirical value and changes between 1.15 and 1.25 [23] and the ROTAP code assumes this value as a constant. After some validation studies, k value is modified as a function of advance ratio as follows:

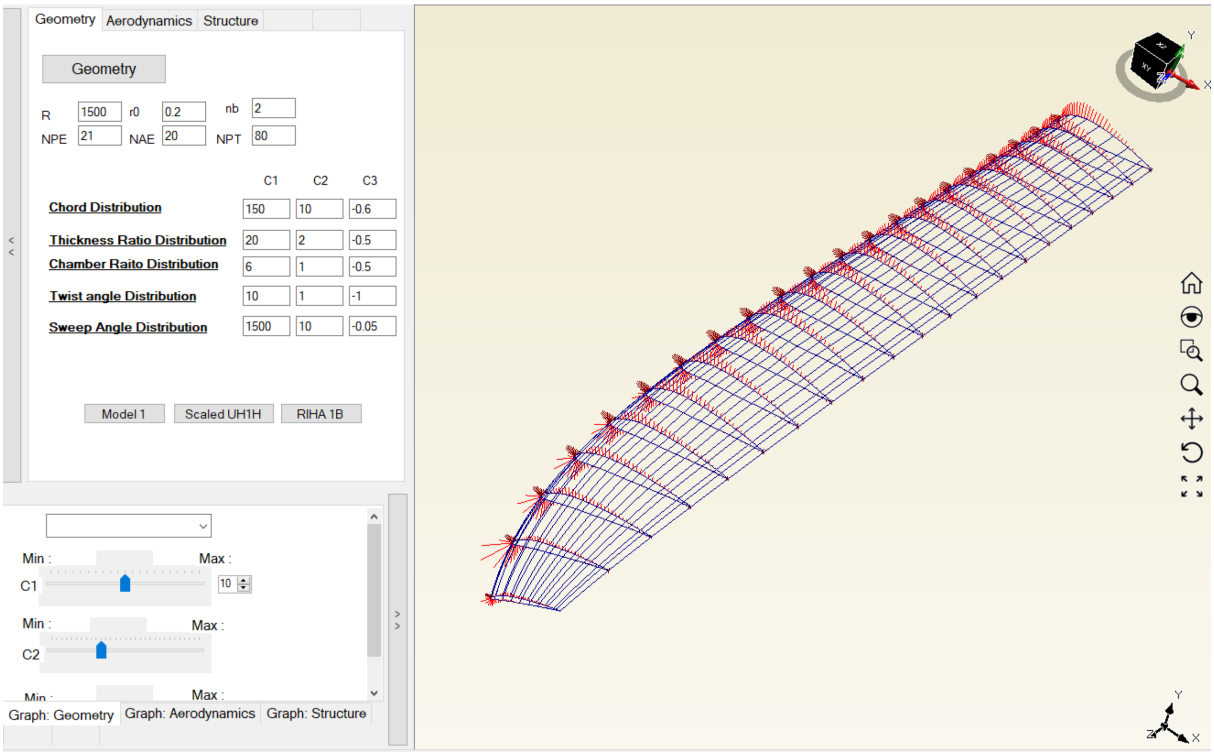
$$k = 1.25 - 2\mu \quad (4)$$

Where μ is advance ratio.

Performance module is modified to obtain airfoil characteristics from panel method analysis instead of look-up tables. Xfoil is currently state of the art panel method code to calculate airfoil characteristics [24]. In this study, Xfoil is modified and related modules for analysis needed in the study are extracted and converted to .dll format. The main purpose of using Xfoil instead of airfoil tables is to increase the number of airfoils available to the design code. When the algorithm chooses an airfoil at a station of the blade, airfoil geometry is automatically generated and lift, drag and moment values for related Mach number and Reynolds number are obtained by the Xfoil library. In addition, Xfoil can obtain pressure distribution (Cp) over the airfoil geometry, which will be useful for further noise level estimations. Performance analysis graphical user interface (GUI) is presented in Figure 9.

3.1. Validation of Performance Analysis

New model is validated by some test results. Sikorsky UH-60 and S-76 helicopter flight test results are used to compare with performance analysis module. UH60 test results (@5250 ft. and W_G=16000 lb.) and S-76 test results (Wind Tunnel Tests and WG=9850 lb.) are obtained from [25] and [26] respectively. Figure 10 and Figure 11 shows comparison between modified ROTAP analysis results and test results of UH 60 helicopters for hover and forward flight cases respectively. Figure 12 and Figure 13 shows results of same performance comparisons for S76 helicopter.



R 1500
r0 0.2
nb 2
NPE 21
NAE 20
NPT 80

	C1	C2	C3
Chord Distribution	150	10	-0.6
Thickness Ratio Distribution	20	2	-0.5
Chamber Raito Distribution	6	1	-0.5
Twist angle Distribution	10	1	-1
Sweep Angle Distribution	1500	10	-0.05

C1 10

Figure 9. Performance analysis screen.

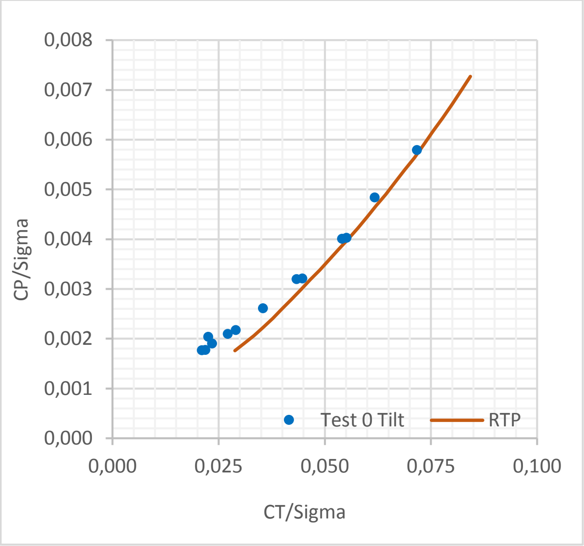


Figure 10. UH60 hover performance analyses and test comparison.

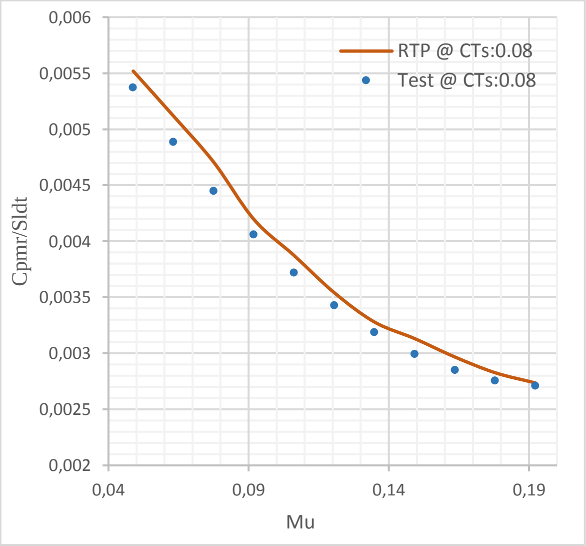


Figure 11. UH 60 forward flight performance analysis and test comparison.

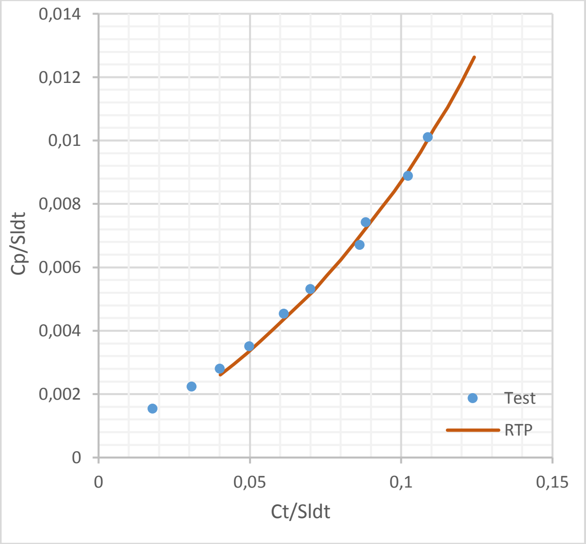


Figure 12. S-76 hover performance analysis and test comparison.

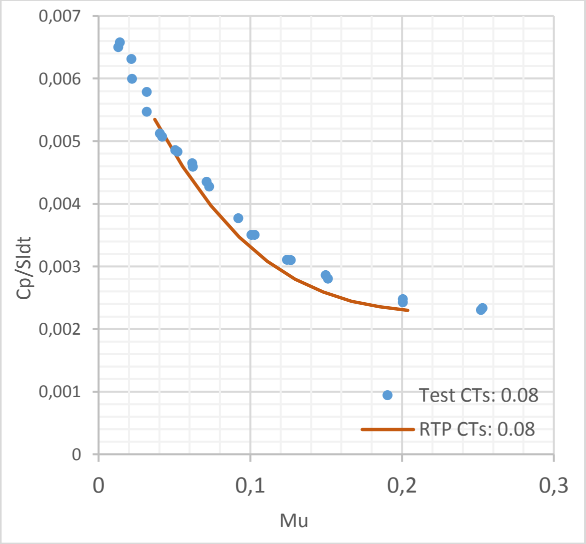


Figure 13. S-76 forward flight performance analysis and tests.

RIHA-1 is an experimental unmanned helicopter platform, which is designed at Istanbul Technical University [27]. The vehicle has maximum 90 kg total weight and ground tests are made on the test bench stand with four load cells. Three of the load cells are used to measure total thrust and moments of the rotor while the last one measures the torque of the rotor. Main shaft is also instrumented with strain gauges to measure the shaft forces. A tachometer measures the rotational speed of the rotor (Figure 14).

Test results are compared with the analysis module results (Figure 15). Main rotor collective was increased from 0 to 70% of max. collective and kept constant at that point (@ 750 RPM constant rotor speed). Measured data and calculated power result with RPM Change can be seen in the Figure 15.

Advanced helicopter concepts are also in the scope of the current study. Therefore, ROTAP performance analysis code is modified for possible new concepts. Trim algorithms are re-modified for compound helicopter concepts, which may include additional lifting surfaces such as wings and additional rotors such as pusher/puller propellers (Figure 16).

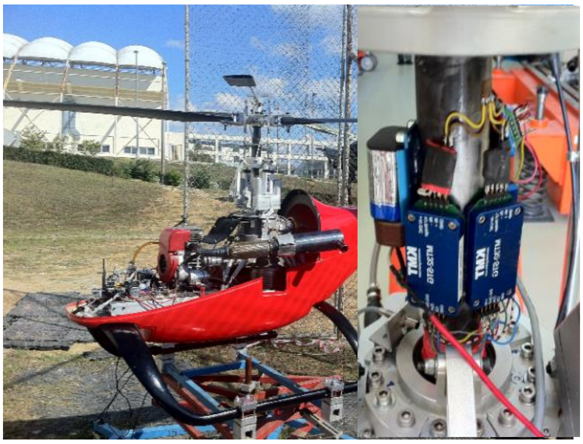


Figure 14. RIHA-1 platform and test benches and instrumentation.

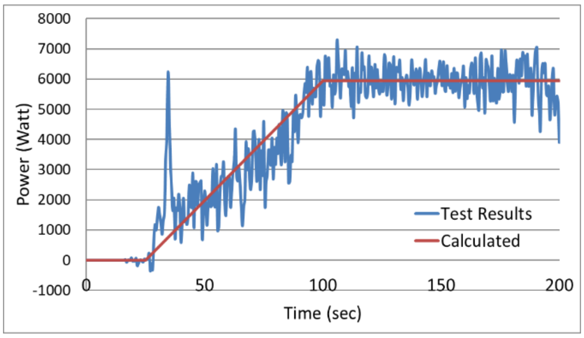


Figure 15. RIHA-1 ground test results and comparison with calculation.

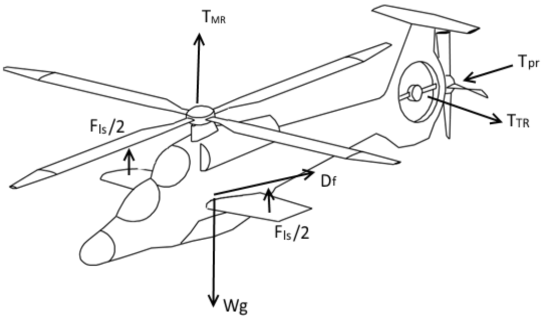


Figure 16. Advanced (compound) helicopter model.

Here, $T_{mr} \geq W_g - F_{ls}$ and $T_{pr} \geq D_f$

Conventional trim algorithms solve six DOF equations to find six unknowns that are collective angles of main and tail rotors, cyclic angles and fuselage position angles in lateral and longitudinal axis. However, an advanced helicopter has more unknowns due to control angles of additional lifting surfaces and additional rotor control and tilt angles. If the rotor rotational speed is variable, then rotor RPM is another unknown for trim algorithm. Therefore, it is impossible to find an exact solution of all control angles and there will be multiple solutions inevitably. In the present study an optimization algorithm is used to solve the trim problem. Algorithm tries to find the best control angles for all the components on the system to get minimal power at the flight condition analyzed as depicted in Figure 17.

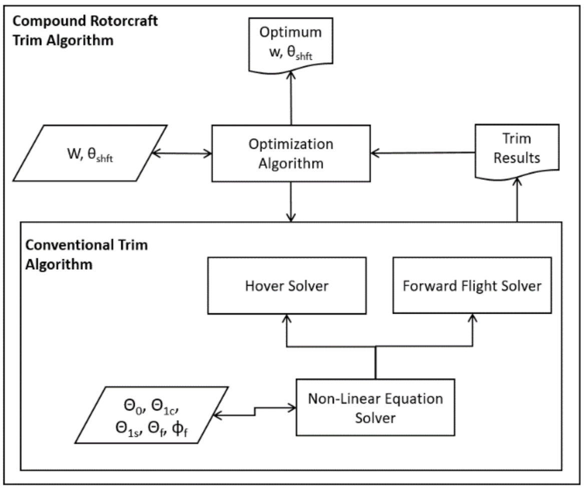


Figure 17. Trim algorithm flow-chart.

An important point is that, the rotor speed and tilt angle do not have to be variable at the same time. In fact, it is customary to assume one of them fixed while the other one is variable. Nevertheless, the developed algorithm does not require such simplifications and it can obtain both parameters. Sample analysis for variable speed rotor is shown in Figure 18, which shows power requirement vs forward flight speed graph at 40 kg takeoff weight.

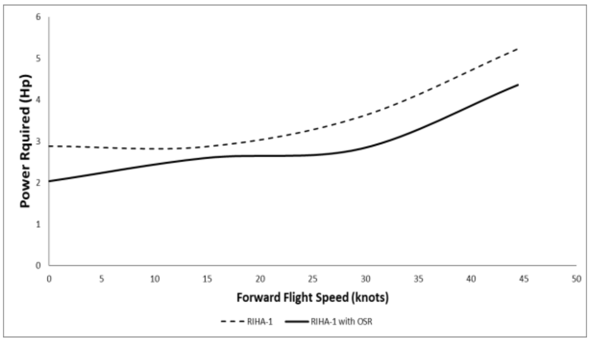


Figure 18. Optimum speed rotor application for RIHA-1.

As it can be seen from the Figure 18, the proposed algorithm can reduce the power requirement at all speeds. However, around 15 knots flight speed, difference at the power reduction is less than other speeds since RIHA-1 original design was already optimized for loiter speed.

Another modification added to the original code is the rigid rotor blade approach. Rigid rotor blade and hub connection works different than the conventional rotor systems because they have no blade flapping motion. Advantages of rigid rotor approach is explained well by Ruddell et al [28] and it is concluded that the main advantage is mechanical simplicity of the design. Rigid rotor systems have no flapping and lead-lag hinges. Absence of these hinges reduces the size, weight and maintenance cost. Another advantage of the rigid rotor is fixed CG location under the loads. Because of the high rigidity of the blade, CG location does not change significantly on the blade that prevents unbalanced force induced vibration of the rotor. On the other hand, moment fluctuation due to unsymmetrical velocity distribution on the rotor at forward flight will pass to the fuselage in rigid rotor systems. Another disadvantage is very large magnitude of bending moments occur at the rotor blade root section that make the structural design difficult and complicated.

4. STRUCTURAL ANALYSIS

Maximum performance is the main target of the rotor design while the blade geometry should have minimum weight. Similar to aerodynamic forces and moments, centrifugal force is one of the main load on the rotor blade and it is the function of blade weight and rotational rotor speed.

It is aimed to design rigid rotors because of their previously mentioned advantages. In the current study rigid rotor is defined by tip deflection and modal frequencies. Tip deflection shall not be more than 3% of the rotor radius under the loads. Also, the first natural frequency of the rotor blade should be at least 3 times the rotational frequency of the rotor. On the other hand, the rotor structure shall not fail under all these loads. Maximum stress and strain under the loads should be lower than allowable values of the material used in design.

Therefore, structural analysis is performed under the following constraints:

- Allowable stress and strains
- Tip deflection or First natural frequency

In addition, it is desired to have a minimum weight structure. Therefore, weight of the blade is a parameter of the design study.

Structural model consists of skin and spar where both are modelled as composite laminates. The variation of number of laminas can be defined as functions that change from root to tip for different materials. The number of laminas, a discrete design variable, is represented by a continuous function in the present study to allow the model to be completely suitable for optimization procedures used.

Similar to blade geometry definition parameters, thickness of the spar and skin can be defined as functions such as power functions in Equation 1. Therefore 3 parameters define thickness variation from root to tip on blade skin or spar. First parameters define the maximum number of laminas, second parameter defines the minimum number of laminas and third parameter defines the variation constant. With this function, number of laminas on the spar or skin can be constant or vary linearly or nonlinearly over the blade from root to tip.

These functions are continuous; however, the number of laminas should be an integer variable. Therefore, the number of laminas on the every station along the blade direction are calculated by rounding the function value to the nearest integer (Figure 19).

Thus, problem could be parametrized by continuous functions with this approach, which simplifies model for optimization algorithms. Material type and orientations of fibers can be different for every layer. However, number of layers may decrease from root to tip. In this case the algorithm should decide which layer will be cut when the number of layers is decreased, automatically. For both spar and skin, pre-defined material types and their orientations are defined by user for optimization algorithms. Maximum number of layers is depicted in Figure 20 as an example.

Top layer of the structure should be continuous and smooth as a manufacturing requirement. Therefore, top layer shall not be cut when the number of layers are decreased. In addition, generally it is preferred to keep bottom layer continuous too. In this case, continuous layers should be selected by user and the algorithm will omit the selected layers when it decides to decrease the number of layers. Results of the inputs in the Figure 20 for the blade spar and skin cross-sections from root to tip can be seen in the Figure 21 schematically. Algorithm cuts the lamina from top to bottom according to thickness function by considering user input lamina list.

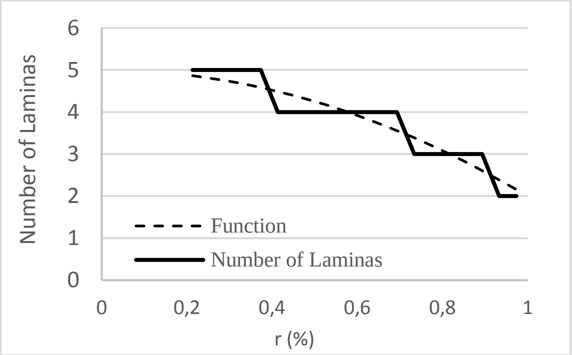
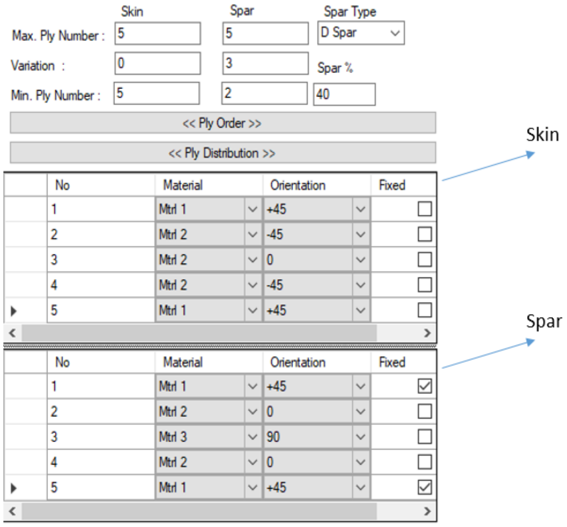


Figure 19. Variation of number of laminas along the example blade.

Spar cross-section shape can be chosen as D type or C type cross-section shapes. Nevertheless, no-Spar option can also be considered on the model (Figure 22). End position of the spar on the chord direction is another variable for calculations.



Max. Ply Number : 5 | 5 | D Spar
Variation : 0 | 3
Spar % 40
Min. Ply Number : 5 | 2

No	Material	Orientation	Fixed
1	Mtrl 1	+45	☐
2	Mtrl 2	-45	☐
3	Mtrl 2	0	☐
4	Mtrl 2	-45	☐
5	Mtrl 1	+45	☐

No	Material	Orientation	Fixed
1	Mtrl 1	+45	☑
2	Mtrl 2	0	☐
3	Mtrl 3	90	☐
4	Mtrl 2	0	☐
5	Mtrl 1	+45	☑

Figure 20. Materials and orientations input window.

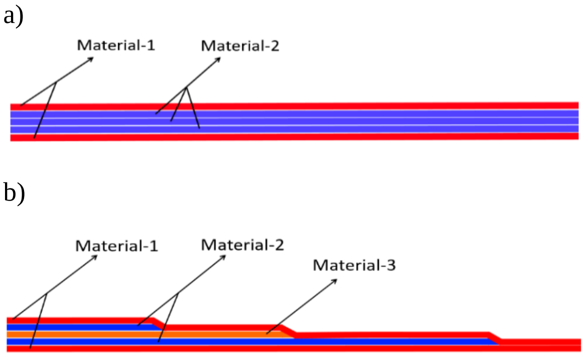


Figure 21. Blade cross sections-layout of laminate from root to tip a) Skin, b) Spar.

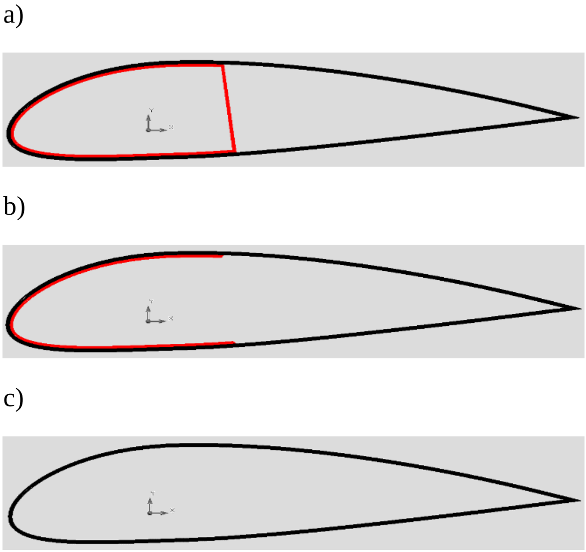


Figure 22. a) D-Spar, b) C-Spar and c) No Spar Options.

Helicopter rotor blades are generally slender structures that are quite suitable for 1D beam analysis. In the literature, there are several beam models already applicable for helicopter rotors. Beam models require minimum computation time and they have sufficient fidelity level especially for preliminary design stages of helicopter rotors. On the other hand, the biggest difficulty related with beam model structural analysis lies in the calculation of cross sectional properties.

4.1. Calculation of Cross-Sectional Properties

Beam analysis requires calculation of stiffness matrices of cross section at several locations over the beam span that depend on geometry and material mechanical properties. Calculation of stiffness matrix analytically for simple geometries and material models such as rectangles and isotropic materials are quite easy. However, most of the helicopter blades are made of composite materials and airfoil geometries are complex. In the literature, there are some methods to calculate blade sectional properties by simplifying geometry and material [29, 30]. Calculation techniques of cross-sectional properties for exact geometries can be classified in two categories. First method is based on Classical Laminate Theory (CLT) while the second and more accurate group of techniques are based on energy methods [31]. Variational Asymptotic Beam Sectional Analysis (VABS) code, is a computer program developed to calculate cross sectional properties of laminated composite rotor blades. This program can calculate 6x6 stiffness matrices of beam cross section that depend on geometry, number of plies and orientations. VABS theory is based on energy methods and its input file is generated by finite element mesh solvers. Every ply and filling material should be meshed with their 3 dimensional mechanical properties. Input files consist of every elements node numbers, material orientations and properties and nodal coordinates [32]. VABS outputs are 6x6 stiffness matrix suitable for Timoshenko beam theory, mass matrix, mass center, principle axes, centroid and the neutral axes.

Usage of VABS is convenient for preliminary design stages. However, an input file for every cross section should be prepared. In the present study, cross section shape and number of lamina changes from root to tip continuously. Therefore, a mesh and VABS input generator is developed and embedded in the code. Blade is already divided into around 20 to 30 number of elements for performance analysis. For all these elements, cross-sectional properties are already calculated. Mesh generator automatically generates the mesh of the cross-sections according to geometry and structure definition functions mentioned above. A sample rotor section mesh can be seen in Figure 23.

4.2. Validation of Cross-Sectional Analysis

Calculated cross-sectional properties are compared with some test and analysis results from the literature. Here the purpose is not the validation of VABS results but the validation of the developed code, which can automatize VABS analysis by creating mesh geometries and input files. Calculated results are compared with the studies made by Wang et al [33]in which proposed model is compared with some test results from the Ref. [34]. Same analyses are followed with the developed code in present study and results are compared.

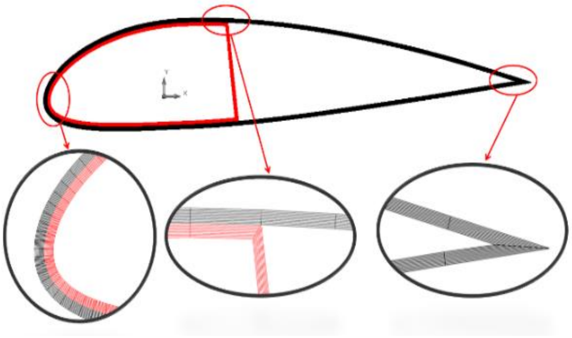


Figure 23. Automatically generated mesh for VABS inputs.

No-Spar Model:

A blade skin without a spar is modelled first. In this model, material is isotropic and geometrical properties, and the geometry are presented in Table 3 and Figure 24 respectively.

Table 3. No-Spar model properties.

Properties	**Value**
E (MPa)	210000
ν	0.3
ρ(kg/m^3)	7850
Airfoil	NACA 0012
Chord (mm)	120
Ply Thickness (mm)	0.675

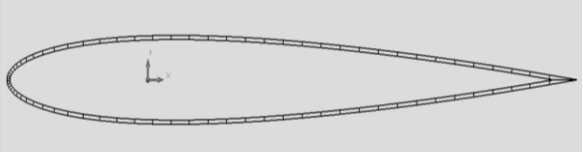


Figure 24. No-Spar model geometry.

Wang et al. compared their own model results with PreComp and Ansys results. All these results are compared with developed model of present study in Table 4. In the table %Diff defines the difference between the results of other codes with Ansys solutions in percentage. Here, RBD (Rotor Blade Design) is the name of the code developed in the present study and CBCAS is the code developed by Wang et al.

Results show that, for all cross-sectional parameters except EI$_y$, developed code has closer results to 3D FEM model results when compared with other codes.

Table 4. No-Spar model results comparison with Ansys model.

	RBD	**CBCAS** [33]	**PreComp** [33]	**Ansys** [33]	**%Diff (Ansys & RBD)**
EA	3.41E+07	3.47E+07	3.47E+07	3.41E+07	0.012
Ei$_x$	867.45	867.56	867.60	866.46	0.115
Ei$_y$	4.10E+04	4.28E+04	4.28E+04	4.07E+04	0.544
GJ	1134.2	1084.8	1085.0	1119.7	1.293
Mu	1.2339	1.2979	1.2980	1.2718	-2.984
I$_x$	3.13E-05	3.24E-05	3.29E-05	3.23E-05	-3.264
I$_y$	1482.5	1602.4	1602.0	1524.7	-2.766

D-Spar Model:

Second validation study is for a composite D Spar rotor blade. Skin has [15/-15] and spar has $[0/15]_2$ layers. Mechanical and geometrical properties are given in Table 5 and Figure 25

Table 5. D-Spar mode properties.

Properties	**Value**
E$_1$ (Mpa)	131000
E$_2$ (Mpa)	9300
G$_{12}$ (Mpa)	5860
ν_{12}	0.4
Radius	NACA 0012
R (mm)	641.4
Chord (mm)	76.2
Ply Thickness (mm)	0.127

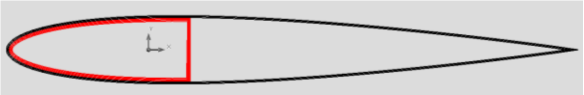


Figure 25. D-Spar blade cross section.

Results are compared with Wang et al [33] and some experimental results from Ref. [34] as presented in Table 6.

Table 6: D-Spar model results.

	RBD	**EXP** [34]	**CBCSA** [33]	**PreComp** [33]	**%Diff (RBD&EXP)**
EA	7.34E+06		8.13E+06	8.13E+06	
Ei$_x$	80.3	77.1	81.4	81.5	4.048
Ei$_y$	3.75E+03		3.45E+03	3.45E+03	
GJ	25.8	25.4	24.4	19.3	1.451

It is observed that the accuracy of calculated cross sectional properties with RBD is satisfactory and much closer to experimental results compared to other codes.

4.3. 1D FEM Analysis

Once the cross sectional properties are calculated for all the sections of the blade, 1D FEM model should be prepared. This model includes cross sectional properties, dimensions and loads. There are various alternative 1D FEM analysis approaches in the literature and the Geometrically Exact Beam Theory (GEBT) developed by Wenbin Yu [35] for rotor blade analysis is selected among them.

GEBT input file contains information on geometrical properties, loads and analysis type. GEBT can carry out 4 different kind of analysis that are static analysis, steady state analysis, dynamic response analysis and eigenvalue analysis. Therefore, tip deflections and natural frequencies of the blade can be calculated using GEBT.

Structural analysis is fully automated since the algorithm can calculate the aerodynamic forces and apply them to do blade structure. Blade geometry can be complicated and blade cross-section can vary from root to tip. Therefore, Algorithm calculates cross sectional properties at all the blade element stations by VABS (Figure 26). Then, GEBT input file is prepared by using loads and cross-sectional properties (Figure 27).

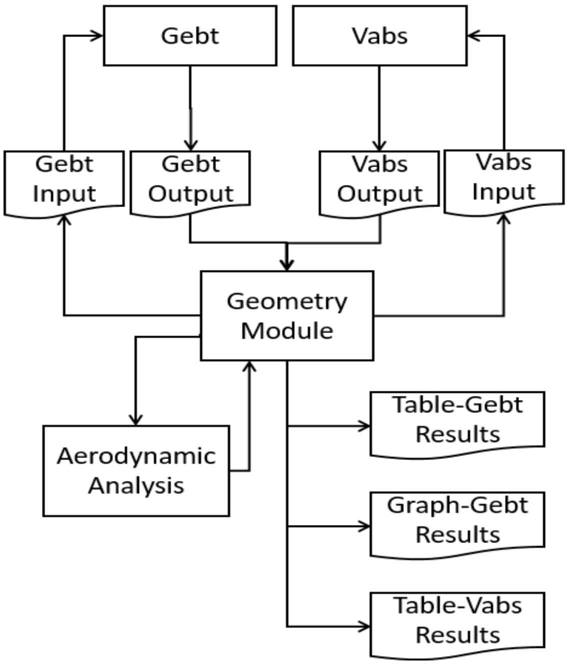


Figure 26. Automated blade structural analysis flow-chart.

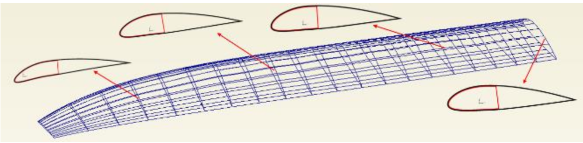


Figure 27. Cross sectional properties at all radial stations are calculated.

4.3.1. Validation of Beam Analysis

Beam analysis results are compared with 3D FEM models. Unmanned rotorcraft model RIHA-1 blades are modelled by both 3D FEM and developed algorithm in the present study. Firstly, material properties are validated with the bending test of the RIHA-1 blade that was produced at the Istanbul Technical University Rotorcraft Excellence Center (ROTAM) (Figure 28).

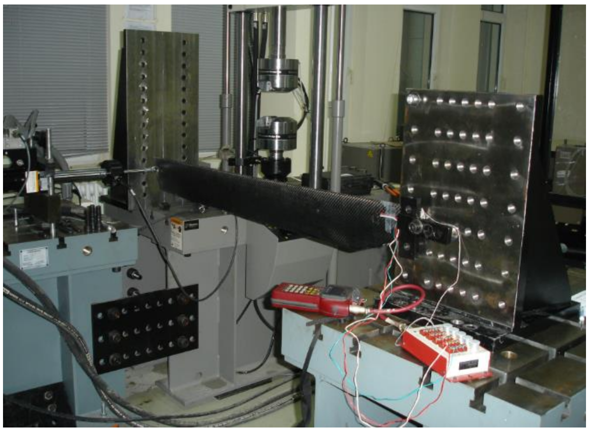


Figure 28. RIHA 1 bending test setup at ITU-ROTAM.

Calculated results for tip deflection with the evaluated material properties and test results are shown in Figure 29.

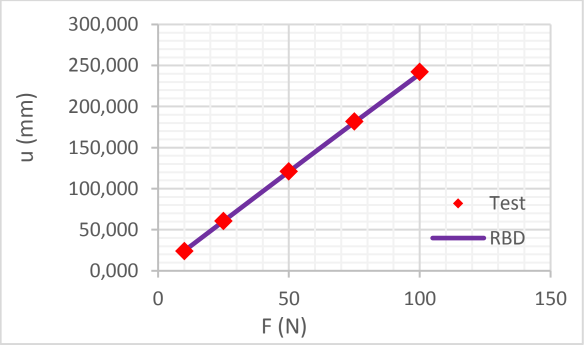


Figure 29. RIHA-1 blade bending test.

After that, a 3D FEM model is prepared by using these properties and analyzed for the loads at three different control angles 5, 10 and 15 degrees. FEM Model is shown in Figure 30 and Figure 31 for loads and interactions and mesh respectively. FEM model, contains 6400 quadrilateral shell elements with 6440 nodes. Aerodynamic loads for all control angles are calculated by developed algorithm and implemented in to FEM model for every individual blade element as concentrated forces to the relevant cross sections at their aerodynamic center points with kinematic couplings. First cross-section of the blade is also connected to the center of the hub with kinematic couplings.

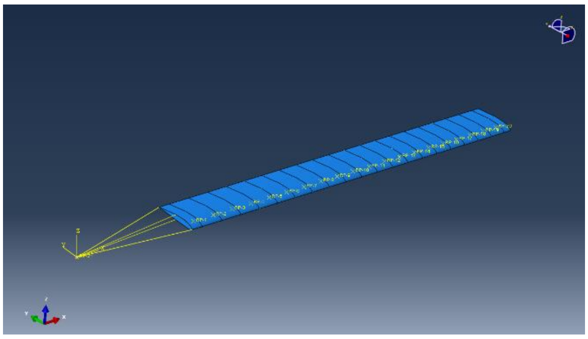


Figure 30. 3D FEM model loads and interactions.

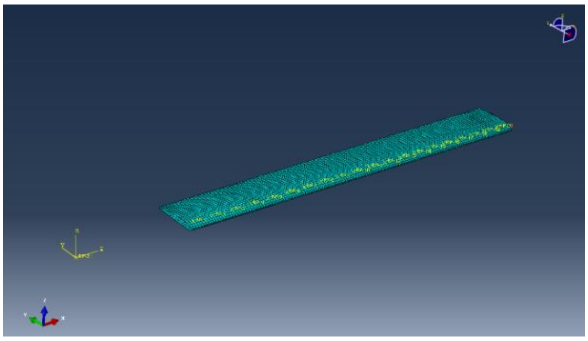


Figure 31. FEM model mesh.

Same model is also considered in the developed algorithm of the current study and results are shown in Figure 32 to Figure 34 for the control angles 5, 10 and 15 respectively. In the figures U represents the deflection of blade.

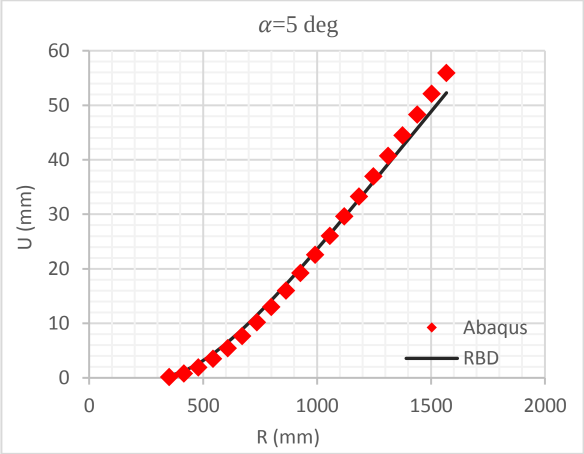


Figure 32. 3D FEM and RBD comparison for the RIHA1 Blade at 5-degree control angle.

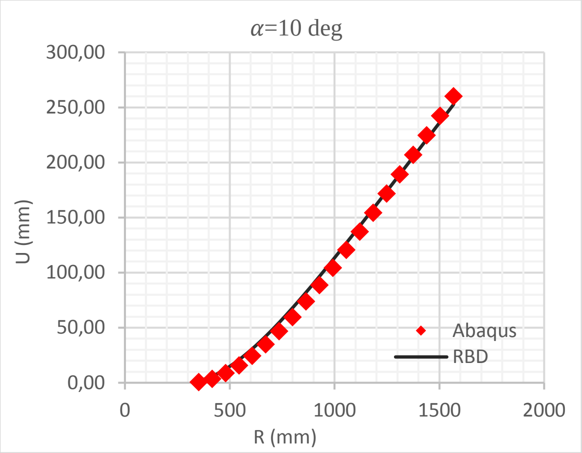


Figure 33. 3D FEM and RBD comparison for the RIHA1 Blade at 10-degree control angle.

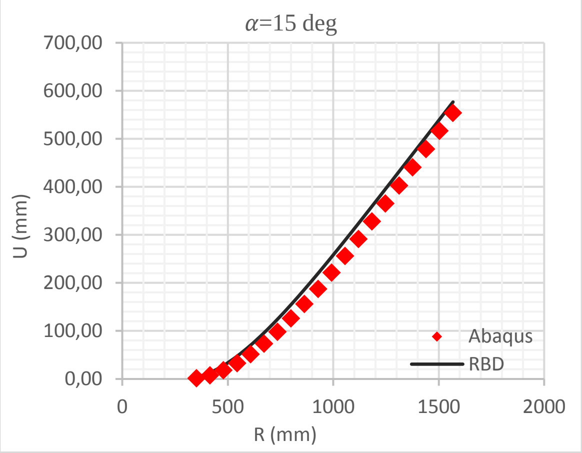


Figure 34. 3D FEM and RBD comparison for the RIHA1 Blade at 15-degree control angle.

Results show that biggest difference between the developed code and FEM is at the tip and around 6.5 %. The results of developed algorithm are sufficiently accurate considering the conceptual design considerations.

5. CONCLUSION

A new methodology for rotor blade geometry definition and multi-disciplinary analysis for advanced helicopter with rigid rotor blades and propeller design is suggested and a design tool fit to this methodology is developed. Proposed design approach is suitable for conceptual and preliminary design stages of the development process. Aerodynamic and structural analyses are coupled for complex rotor blade geometries. Developed tool can analyze the system fully automatically by the help of some in house, open source and trade codes used together. In addition, the developed code is designed to work together with optimization algorithms. Thousands of alternative concepts can be evaluated in a very short time by the help of this tool because of reduced number of parameters for complex blade geometry and structure in the developed algorithm. Noise level estimation analysis algorithms may also be embedded inside the tool in the future studies. Moreover, the proposed framework has potential to be the foundation of composite rotor blade multidisciplinary optimization studies.

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