AUTOMATED MODEL BASED CONCEPTUAL DESIGN APPROACH FOR COMPOSITE HELICOPTER ROTOR BLADES

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Abstract

In this paper, an automated conceptual structural design methodology of composite helicopter rotor blades is described. Furthermore, design outputs such as blade weights of commercial aircraft blades are compared with the outputs of the tool using this methodology. The methodology applied targets to find optimum internal structure which can compensate outcomes of major rotor design parameters which are chord length, rotor radius and rotor frequency. Minimum blade weight is objected while searching necessary internal structure. Structural integrity and cross-sectional center positions affecting dynamic responses are constrained while searching for the necessary internal structure. The method applied differs from traditional blade optimization studies with the solution time and maximum parametrization of blade structural configuration. Hence, method does not target to optimize a blade structure having a detailed initial design. It aims to find a feasible design from sweep models of blade configurations with necessary mass attachments.

1. INTRODUCTION

Rotor blade design is one main challenging part of helicopter design because of the multidisciplinary behavior of blades. Moreover, manufacturing constraints and high-cost of production are the other main considerations for the blade design. Many analysis methods, tools, and optimization techniques are ready to use in literature and industry for detail design in terms of dynamics, fatigue, ballistic tolerance etc. However, structural designers commonly need a good starting point for the design at the early design stages when main rotor parameters such as blade surface geometry, rotor radius and rotation speed are defined by aerodynamics and performance engineers. Moreover, fast and feasible initial structural design estimation lets helicopter aeromechanical, load calculation and dynamic studies to start with a sufficient precision. Furthermore, production cost of the blades can also be predicted from the initial structural design.

In literature, there exist various studies investigating conceptual design phase of composite helicopter rotor blades. There are several studies focusing on structures besides aerodynamics and performance. Earlier studies commonly used statistical methods to predict main rotor blade weight[1]. Unsworth and Sutton[2] predicted main rotor blade weight by statistical, semi-analytical and analytical methods. While they use only database including rotor radius, chord, tip speed, margin of safety, and advance ratio values of helicopters to predict blade weight. The improvements on blade weight estimations are achieved by semi-analytical and analytical with the help of computer technologies.

Recent studies tend to analysis-based estimations. In the study of Ngoc Anh Vu and coworkers[3], performance, aerodynamics, and structure are coupled and considered in one fully automated design optimization of rotor blades. A D-spar cross-sectional blade having realistic inner configurations including thicknesses of D-spar, skin, web, number and ply angles of layers of each composite part, and materials are analyzed during optimization. A number of codes and commercial software (ANSYS, Gridgen, VABS, PreVABS, etc.) are implemented to automate the structural analysis from aerodynamic data processing to sectional properties and stress analysis.

Composite materials have been widely used in helicopter rotor blades due to the high specific strength and damage tolerant capability. Moreover, usage of composite materials creates flexibility to tailor the blade structural properties and rotor dynamic responses which is perhaps the most significant advantage of composite materials.

There exist studies investigating the effects of composite blade configurations on blade structural properties and rotor dynamic responses. In the study of Salkind and Geoffry[4], the design advantages of fiber-reinforced composites in

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

helicopter rotor blades are investigated. The authors stated that increasing the quantity of fibers oriented at ±45° with respect to the blade span leads to a significant increase in the torsional rigidity with a small change in the first flap and lag frequencies. Moreover, using ±45° plies gives the advantage of satisfying high specific torsional stiffness for the blade skins. Application of high modulus composites is more advantageous than glass-epoxy composites for tuning torsional and bending stiffness. The reason is that torsional stiffness can alter with a minimum polar moment of inertia change for high modulus materials.

One of the most extensive study has been done by Li and Volovoi[5]. They studied the effects of blade cross-sectional design parameters on the blade stiffness and mass properties. Seventeen number of design variables are utilized in sensitivity analysis. In order to generate the data pool, the authors used the principles of Design of Experiments (DOE). Box-Behnken and Eight Fractional Factorial methods were employed for the data generation. The objective of the sensitivity analysis was to quantify the relative effectivity of each blade design parameter on blade structural properties.

Bilen and Isik[6] investigated the contribution of various blade structural design parameters on the blade cross-sectional properties. These are number of UD spar plies, the radius of cylindrical nose weight, chordwise distance of spar wall from the leading edge, the angle of middle cross-plies of the skin, number of outer-wrap ±45° cross-plies and the number of UD skin support plies mounted at trailing edge side of the cross-section. Results show that wall location is effective in most of the responses. Number of trailing edge support plies is a very effective parameter in all chordwise and in-plane dominated parameters. Skin lay-up angle provides significant changes to the blade structural properties and maximum spanwise strain. Number of spar plies is the most effective on blade spanwise properties such as axial stiffness and maximum spanwise strain. Nose weight radius is not affective on blade structural properties except sectional mass related center positions.

In the previous helicopter rotor design and optimization studies[7], [8], [9], [10], [11], [12], [5] the distance between chordwise center of gravity position (CG) and chordwise shear center (SC) is taken into consideration during the blade design. These studies stated that increasing the distance between SC and CG leads to aeroelastic instability, a mix of vibratory modes and an increase in pitching moments. Furthermore, if the neutral axis (NA) and the SC gets closer to the FA, which coincides with aerodynamic center, strain contribution due to the eccentricity of the NA and the SC decreases.

In this study, an automated conceptual structural design methodology of composite helicopter rotor blades is described. The applied methodology targets to find the optimum internal structure, which can compensate outcomes of major rotor design parameters that are chord length and rotor radius. A stepwise design and optimization methodology is defined. In the first step, a detailed cross-section of the functional region of the rotor blades has been modeled. Six pre-determined influential design parameters including chord length and rotor radius are investigated. For this, a set of design parameter combinations are analyzed to obtain cross-sectional properties, namely blade stiffness, blade weight, cross-sectional centers for the functional region. Using these properties, root and tip properties are scaled, spanwise property distributions are obtained, and necessary mass attachments and damper properties are calculated. Load calculation is conservatively calculated for a rotor model under vacuum to calculate maximum cross-sectional strain. Sweep models are created between design inputs and structural properties with strain outputs. In the second step, an optimization is performed for a constant rotor radius and chord length. These parameters are assumed determined in the conceptual phase. Optimization uses rest four internal structure parameters as variables and targets to minimize blade weight. Cross-sectional centers and maximum spanwise strain are constrained to find a feasible and conservative solution. Quick solutions as structural conceptual design are found because sweep models are used in optimization function.

Various commercial helicopters having literature data are also studied to compare with the estimation. Moreover, sectional properties of a conceptually designed helicopter are compared with estimated sectional properties.

2. MODELLING

2.1. Cross-Sectional Modelling

Concerning the blades used in this study, Figure 1 shows the baseline model of the cross-section having a VR-12 airfoil. As it can be seen from Figure 1, the functional region of the blade contains detailed parts including the D-Spar, skin, erosion shield, heater material, film adhesive and the honeycomb core.

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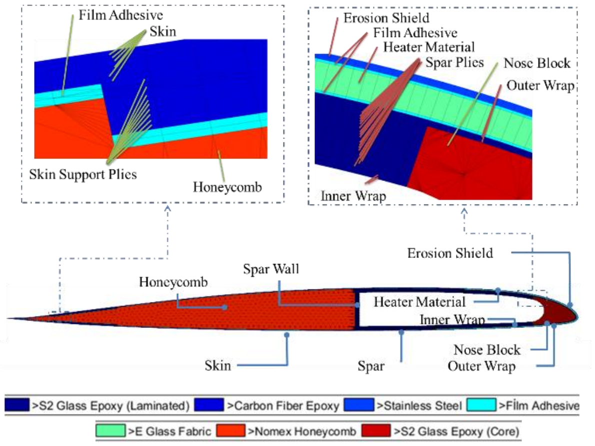

Figure 1. Cross-sectional model of the functional region

The spar is composed of spar straps, inner-outer wraps, spar wall and nose block. Spar straps, nose block and spar wall are covered by inner and outer wraps. For all spar components glass-fiber material is used. While spar straps and nose block are composed of UD plies; spar wall and inner-outer wraps are composed of ±45° cross-plies. The skin is composed of carbon-fiber epoxy cross-plies. Additional UD carbon-fiber epoxy support plies are attached to the skin at the trailing edge side of the functional region. Due to the high velocity air flow, a stainless-steel erosion shield is attached to leading edge side of the functional region. Just under the erosion shield, an E-glass heater material is modeled for deicing. Finally, a honeycomb completes the sandwich between upper and lower skin.

Five significant design parameters of the cross-section configuration are taken as variables to be utilized in parameter sweep. Each parameter is gridded to construct sweep models. An example case for two-dimensional gridding is illustrated in Figure 2.

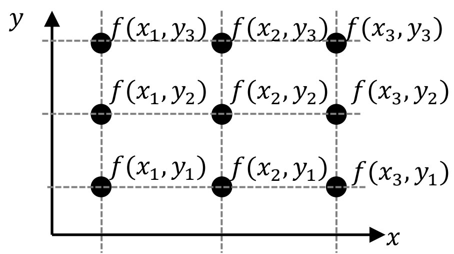

Figure 2. Illustration of gridding for two-dimensional case

The grid points used in this study are given in Table 1 and they are illustrated in Figure 3.

Table 1. Grid points of cross-sectional design parameters

Parameter	Grid Points	#Grid Points	Unit
c	300, 425, 550	3	mm
SP	8, 22, 36	3	-
SL	3, 5	2	-
SSW	0.25, 0.325, 0.4	3	mm/mm
TS	0, 3, 5, 7, 10	5	-

SP is defined as number of UD spar plies. SSW is the nondimensional spar strap width, which is bounded by nose block on one side and spar wall on the other side. The strap width is centered at feathering axis because spar straps are centered symmetrically at root of the blade, which is a design constraint. Hence, cross-sectional position of nose block and spar wall is determined by SSW parameter. SSW is nondimensionalized by chord (c). SL is the number of skin plies. The layup configuration of skin is defined as [45°/90°/-45°] for the three plies condition and [±45°/±SL°/±45°] for the five plies condition. Finally, TS refers to the number of UD skin support plies. The rest of geometric parameters such as erosion shield position are defined as constant function of chord length. Cross-section analysis has been performed for the combinations of grid points for each design parameter.

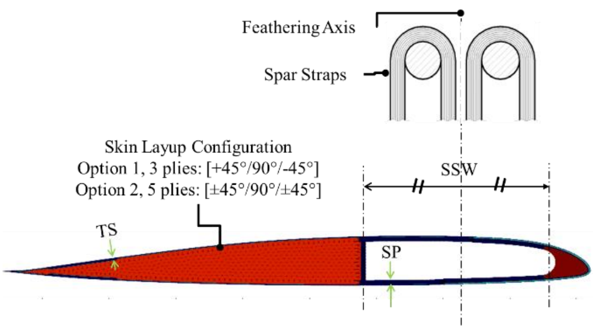

Figure 3. Cross-sectional design parameters

In this study, the helicopter blade is modeled as a beam consisting of 2D cross-sectional FE model. This model is generated by a combination of an automated core mesher and PreVABS[13] and analyzed by VABS (Variational Assymptotic Beam Section Analysis) solver[14]. PreVABS is a design-driven, pre-processing computer program which can effectively generate high-resolution finite element modeling data for VABS by directly using design parameters such as simple geometric parameters and both the spanwisely and chordwisely varying composite laminate lay-up schema for rotor blade. Automated core mesher creates the mesh generated for the honeycomb

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core, the nose block and the cylindrical nose weight and merges with the PreVABS mesh. The applied meshing is originated from the method used in the study of Isik and Kayran[15] which is specialized for cross-sections having D-Spar, trailing edge, nose block and nose weight cores. Developed by Cesnik and colleagues, VABS can perform classical analysis for inhomogeneous, anisotropic beams with initial twist and curvature having arbitrary reference and material properties yielding stiffness and mass matrices. Moreover, the three-dimensional stress and strain fields can be recovered using VABS.

Cross-sectional properties of the beam blade, such as the neutral axis, shear center, stiffness and mass matrices calculated by VABS are defined with respect to the reference axis S_{ref} to be used in dynamic analysis. The reference axis system S_{ref} is demonstrated in Figure 4 and its components are explained in Table 2. It is to be noted that “2” and “3” vector components of S_{ref} has the same meaning of chordwise and flapwise direction terms, respectively.

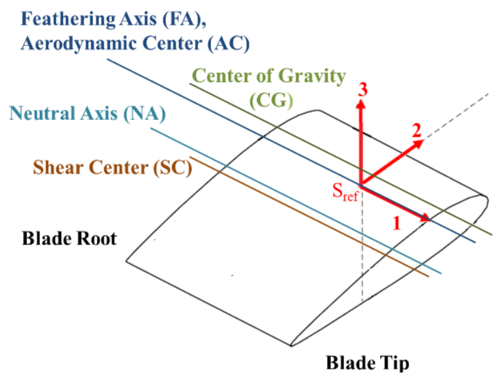

Figure 4. Blade reference axis system

Critical centers used in this study are the center of gravity (CG or mass center), the neutral axes (NA or tension center), and shear center (SC or the elastic axis). x_{CG} is the location of chordwise CG. x_{SC} is the location of chordwise SC. x_{NA} is the location of chordwise NA. In this study, the Aerodynamic Center (AC) is assumed intersecting with Feathering Axis (FA).

Table 2. Components of Blade Reference Axis System

Origin	Intersection of spanwise station and the FA
1-direction	Direction towards the blade tip from the blade root coinciding with the FA
2-direction	Parallel to chord line towards leading edge (Chordwise)
3-direction	Towards the upper surface obeying the right-hand rule (Flapwise)

2.2. Rotor Model

In this study, a four bladed, fully articulated rotor is investigated. The rotor is assumed to be in vacuum and is fixed to the ground with rigid connections. It is to be noted blade loads are not affected by the number of blades since aerodynamic forces are neglected.

The rotor model is based on the study done by Bilen[16]. The rotor is equipped with non-rotating actuators, swash plate, pitch link, and pitch control lever and lead-lag damper. Swashplate rotation is provided with scissors attached to the mast. Articulation is provided with spherical bearings which connect the blade to the hub with the help of tension links. Since articulation is provided by a spherical joint, lag, flap and pitch hinges are coincident. The blades are modeled as one-dimensional beams. In Table 4, basic rotor parameters are provided. Rotor radius (R) is a variable in the scope of this study. Hence, length and position of each rotor equipment is a function of R in the model. The grid points used in rotor model for varying R is defined in Table 3.

Table 3 Grip points of rotor design parmeters

Parameter	Grid Points	#Grid Points	Unit
R	4, 6, 8, 10	4	m

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Table 4. Rotor parameters

Number of Blades	4
Tip Speed	226 m/s
Rotor Speed, Ω	$Tip\ Speed/R$
Hinge Offset	$0.05\ \eta$
Root Cut-out	$0.09\ \eta$
Functional Region Start	$0.25\ \eta$
Tip Start	0.90η
Airfoil Profile	VR-12
Torque Offset	-
Pitch-Flap Coupling	10°, pitch up nose down
Twist Rate	$6°@0.25\ \eta, -2°@\ \eta$

The model is developed with Dymore, a finite element based multibody dynamics code for the comprehensive modeling of flexible and nonlinear multibody systems[17]. Dymore utilizes three-dimensional geometrically correct beam theory for modeling the beams. Detailed description of Dymore and its beam formulations can be found in in the references[17], [18].

3. METHOD FOR MODEL CONSTRUCTION

In Figure 5, the input-output relations of blade design parameters, and model outputs. The parameters in red boxes are used in optimization step given in next section. These outputs are critical center positions of the functional region, blade weight, and maximum strain in spanwise direction.

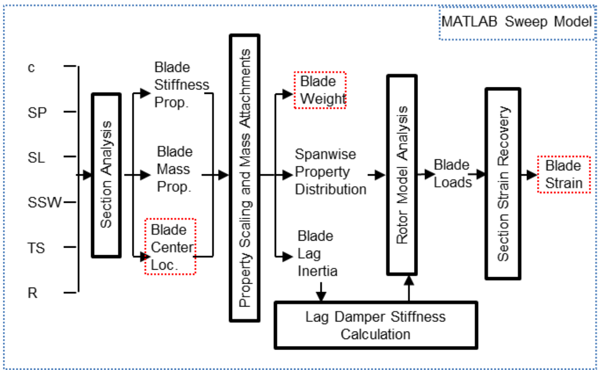

Figure 5. Analysis Flowchart

The cross-sectional analysis applied to the functional region requires six inputs and the analysis results in a fully-populated, symmetric 6×6 stiffness matrix as well as sectional mass properties and center locations. Root and tip region properties are scaled from the properties obtained by cross-sectional analysis of the functional region. Spanwise starting position of the functional region is symbolized as 0.25η. A conceptually studied helicopter main rotor blade properties are used as reference scaling factors in this study. The scaling formulations are given in Eqn. (1) and Eqn. (2).

$$(1) \qquad p_{Des@i} = \frac{p_{Ref@i}}{p_{Ref@0.25\eta}} * p_{Des@0.25\eta}$$

$$(2) \qquad x_{Des@i} = \frac{x_{Ref@i}}{c_{Ref@0.25\eta}} * c_{Des@0.25\eta}$$

where p refers to the sectional mass or stiffness property, x refers to the critical center position, c refers to the chord length. p, x and c values for design (Des) at i'th η are calculated from reference blade (Ref) values and design properties at 0.25η.

Spanwise property and center position distributions are obtained by root and tip property scaling to be used in rotor model. However, chordwise cg tuning for aeroelastic stability and static balance weight application are the effective mass attachments while calculating blade loads. Mass attachments applied analytically to the spanwise property distributions are shown in Figure 6.

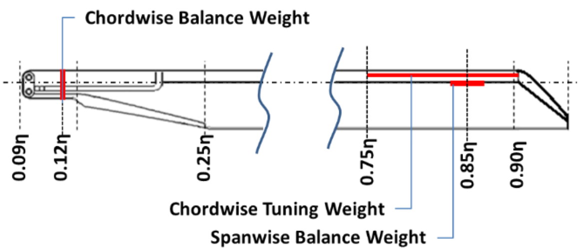

Figure 6 Mass attachments

Chordwise tuning weight is initially applied at between 0.75η and 0.90η in spanwise direction and $0.20\ c$ through leading edge in chordwise direction. It is assumed to be embedded in nose block. In this study, dynamic instability can be caused only by aeroelastic phenomenon occurring close to the tip because of high airflow speed. Considering this, only integrated CG between $0.75\ \eta$ and $0.90\ \eta$ is investigated and tuned. Necessary weight to shift chordwise center of gravity position on feathering axis is calculated.

2% and 0.5% of recently obtained blade weight is used as spanwise and chordwise balance weight, respectively. The weights both centered on FA.

Damper stiffness is one of the main parameters effecting on blade loads especially on chord bending moments. In the thesis of Bilen[19], the first lead-lag mode frequency (ω_ζ) is targeted to be $0.40/rev$ in order to reduce the necessary damping required for ground resonance stability. The necessary damper stiffness to achieve target frequency for articulated rotor blade is formulated

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as given in Eqn. (Error! **No text of specified style in document.**3)[20].

$$K_D = \frac{I_\zeta(1 - e/R)}{b^2}\left(\omega_\zeta{}^2 - e\frac{S_\zeta}{I_\zeta}\Omega^2\right) \quad \text{(**Error! No text of specified style in document.**3)}$$

where K_D is the spring coefficient of the lag damper, e is the lag hinge offset, S_ζ and I_ζ are the first and second mass moment of inertia of the blade about lag hinge, b is the shortest distance between lag damper line-of-action and the lag hinge, and Ω is the rotor speed. The geometric parameters (b, e, R) are the functions of rotor radius which are set in the rotor model. Since final mass property distribution of the blade is known S_ζ and I_ζ are also calculated and used in the equation.

For each blade design configuration using the final spanwise distribution of stiffness, mass, center information and damper stiffness, rotor model analyses are performed. The eigenvalue solution gives the rotor frequencies as well as the mode shapes associated with those frequencies. However, frequency tuning is not in the scope of this study. The tuning is assumed to not increase blade weight resulting increase in blade loads because target frequencies can be reached by mass removal during optimization in detailed design phase.

The blade loads, which are calculated for the blade model in vacuum, are magnified to cover the overall flight conditions. It is assumed that rotor works with 200% of its operational speed while magnifying the loads[21]. Magnified loads are used for and the strain calculation step.

Although every parameter can be used in sweep model as outputs, only three of them are set as final model output to be used in design selection. Blade weight (M_b) is targeted to minimized while constraining maximum strain (ε) and center positions. The center positions are the chordwise locations of center of gravity x_{CG}, neutral axis x_{NA} and shear center x_{SC}.

Analysis resulted in $3 \times 5 \times 3 \times 2 \times 3 \times 4 = 1080$ blade design combinations

The total list of investigated variables and their short descriptions are provided in Table 5.

Table 5. Parameters used in Sweep Model and their descriptions

	Parameter	Description
Blade Design	c	Chord Length
	SP	Number of Spar Plies
	SL	Skin Lay-up Configuration
	SSW	Spar Strap Width
	TS	Number of Trailing Edge Support Plies
	R	Rotor Radius
Sectional Outputs	EA	Axial Stiffness, $[N]$
	k_{22}, k_{33}	Chordwise and Flapwise Shear Stiffness
	GJ	Torsional Stiffness, $[Nm^2]$
	EI_2, EI_3, EI_{23}	Flapwise, Chordwise, Cross Bending Stiffnesses, $[Nm^2]$
	m_0	Mass per Length, $[kg/m]$
	m_1	Polar Inertia, $[kgm^2/m]$
	x_{CG}, x_{NA}, x_{SC}	Center of Gravity, Neutral Axis, and Shear Location $[mm]$
	ε	Maximum Strain in Spanwise Direction $[\mu Strain]$
Blade Outputs	M_b	Blade Weight $[kg]$
	I_ζ	Second Mass Moment of Inertia About Hinge$[kgm^2]$
	S_ζ	First Mass Moment of Inertia About Hinge$[kgm]$
	K_D	Damper Stiffness, $[N/m]$

4. METHOD FOR OPTIMIZATION

Conceptual design methodology targets to find minimum blade weight for selected chord length (c) and rotor radius (R) considering the design constraints. The design constraints are designated as maximum strain in spanwise direction and chordwise positions of critical cross-sectional centers. The optimization flow chart is given in Figure 7. The optimization directly uses the preconstructed sweep model functions to find optimum design rapidly.

Matlab GA toolbox[22] is utilized due to its high-fidelity and integer variable capability considering the integer variables (SP, SL and TS).

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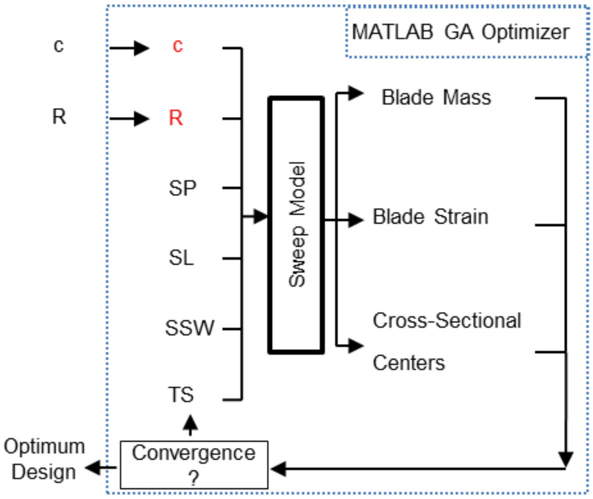

Figure 7 Optimization Flow Chart

The design variable constraints are then defined as maximum and minimum bounds of design grid points as

(4) $$8 < SP < 36$$

(5) $$1 < (SL - 1)/2 < 2$$

(6) $$0.25 < SSW < 0.40$$

(7) $$0 < TS < 10$$

For the strength constraint, maximum strain criterion is chosen. For carbon epoxy material, which has the minimum UTS capability among materials used in blade modeling, UTS value is given as 13200 μStrain by Samborsky and coworkers[23]. However, considering the impurities, notch sensitivity, material defects, debonding and fatigue behavior, in the present study maximum strain in spanwise direction is taken conservatively as 5400 μStrain by Isik and Altan[21] for the optimization of a main rotor blade having initial design. However, in this study, it is aimed to be more conservative since the loads applying on the blade can increase during the optimization and dynamic tuning stage of the blade. It is to be noted that other strain limits are tested while mass estimations of commercial aircrafts given in results section.

(8) $$\varepsilon < 5000\ \mu\text{Strain}$$

In the present study, 3% chord length eccentricity from the FA is accepted for the CG, SC and the NA in the chordwise direction. Previously, chordwise positions of the sectional centers are nondimensionalized by chord length c as given by Eqn. (9) - Eqn. (11),

(9) $$-3\% < x_{CG}/c < 3\%$$

(10) $$-3\% < x_{CG}/c < 3\%$$

(11) $$-3\% < x_{CG}/c < 3\%$$

where CL is the chord length of cross-section, x_{CG} is the location of chordwise CG, x_{SC} is the location of chordwise SC and x_{NA} is the location of chordwise NA.

Objective function is defined by Equation (12). In Eqn. (12), weight function f is subjected to constraints through the penalty parameter (r) resulting in the augmented objective function Φ. Normalized values of the weight function and the constraints are used, because it is desired to penalize the weight function in a similar order of magnitude due to the constraint violation.

(12) $$\Phi = f + r * \left(\sum_{k=1}^{N} Constraint_k{}^2\right)$$

Blade weight (M_b) is normalized by dividing blade weight with an average value of commercial aircraft main rotor blade weights as shown in Eqn. (13).

(13) $$f = \frac{M_b}{Average\ Blade\ Weight}$$

Suitable penalty parameter (r) is taken as 1000 after adequate number of trials performed.

Normalized constraints for the outputs of these two models are formulated as given in Eqns. (14) - (17). The normalized constraint equations are set as inactive for the negative results which means that the problem is in feasible region for the relevant constraint.

(14) $$Constraint_1 = max\left(0\,, \frac{(x_{CG}/c\,) - 0.03}{0.03}\right)$$

(15) $$Constraint_2 = max\left(0\,, \frac{(x_{NA}/c\,) - 0.03}{0.03}\right)$$

(16) $$Constraint_3 = max\left(0\,, \frac{(x_{SC}/c\,) - 0.03}{0.03}\right)$$

(17) $$Constraint_4 = max\left(0\,, \frac{\varepsilon - 5000}{5000}\right)$$

For the CSO, the convergence criterion is set as the maximum number of iterations after performing several trials on case studies. The convergence is assumed to be reached according to the difference in the augmented objective function Φ between CSO iterations. If the difference in Φ between the last iteration and 3 iterations before the last iteration is less than 10^{-4}.

5. RESULTS AND DISCISSON

In this section, the applicability of the method constructed is investigated. Rotor radius and chord length data of commercial aircrafts are collected from the literature[24],[25],[26]. Main rotor blade weights of several helicopters are predicted for

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corresponding R and c values. Moreover, cross-sectional properties and critical center positions of reference blade and its estimated values are compared.

In Figure 8, main rotor blade weight data of commercial aircrafts and conceptually designed reference blade are compared with the main rotor blade weight outputs obtained from the concept design process. The effect of maximum strain limit used in optimization process is also investigated. The results show shat, for commercial aircrafts, setting strain limit as 5200 μStrain gives feasible results while 5000 μStrain gives the best result for the reference blade.

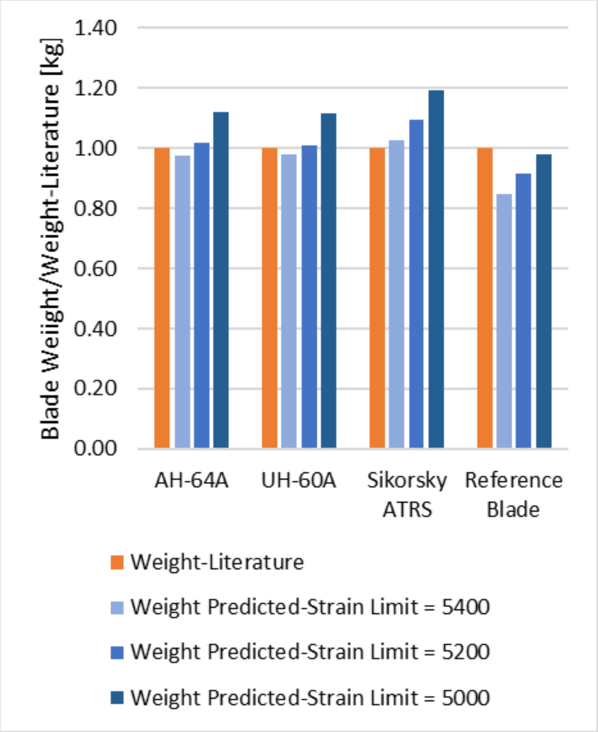

Figure 8 Blade weight estimation results

In Figure 9, normalized properties of reference blade and its estimated results obtained from concept design methodology are compared. Average property values of the functional region between 25% η and 75% η are used as the reference blade property values. EA, EI_{22} and $m11$ have significant difference between reference blade and estimated properties. It is to be noted that these results are expected because no drop-offs and spanwise optimization is applied in the concept design methodology.

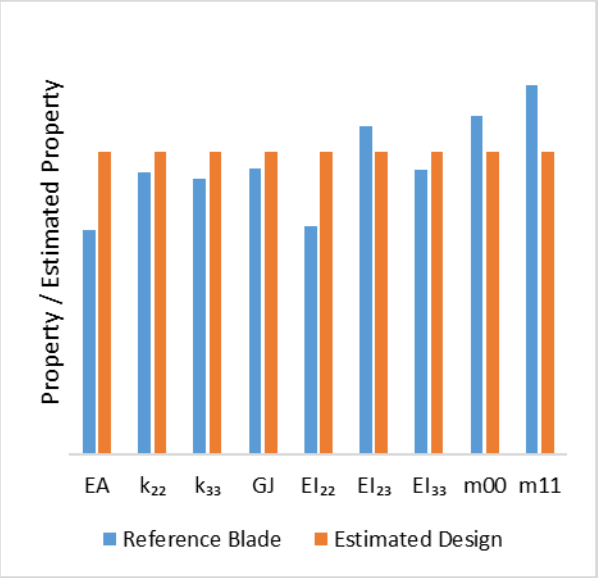

Figure 9 Property estimation results

Normalized results of center positions are given in Figure 10. 5000 μStrain limit is chosen to stay conservative. Center positions are normalized by chord length c. Although the data to compare amplitudes is not sufficient, it can be seen that the directions of center positions are the same for the reference blade and estimated properties.

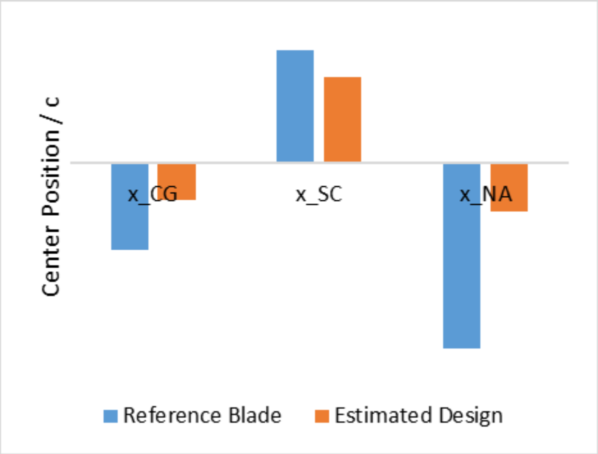

Figure 10 Cross-sectional center estimation results

Concept design methodology results end up with the following conclusions

1. Overall methodology gives reasonable estimations considering the blade weight, sectional property and center positions comparisons for corresponding rotor radius and chord length values.
2. Maximum strain limit is an effective parameter on design estimation. If lower values are used, a conservative starting point to design can be achieved. The best

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limit can be achieved by high experience of blade design studies.
3. In the case of staying conservative while selecting maximum strain limit, estimated blade weight increase. Although it seems infeasible, the blade weight will decrease in detail design stages because weight reduction of internal structure is applicable.
4. The design prediction time spent by the optimization is less than one minute. This rapid solution time is expected because sweep model functions are used.

This study can be enhanced in terms of solution time, expanding the design grid points and torsional tip defamation check. First, a more efficient optimization approach can be investigated for the CSO optimization instead of GA used. Although GA is robust and applicable to the integer variables, the optimization efficiency still can be increased by other algorithms. Secondly, the design space is limited because grid points do not cover every possible rotor radius and chord length parameter. Increasing the number of grid points will expand the design search area for helicopters. Finally, blade deformation under torsion is another important aspect for the blade design. Number of skin plies can easily tailor this parameter. However, the deformation cannot be obtained because aerodynamic loads are omitted in this current study. If a relation between design parameters and torsional deformation under aerodynamic loads is achieved, this relation can be embedded in the concept design methodology.

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Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019