



Cairo University

# **AERODYNAMIC SHAPE OPTIMIZATION OF HELICOPTER ROTOR BLADES**

By

**Sameh Al-Sayed Hilal Darwish**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Aerospace engineering**

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**Title of Thesis:**

Aerodynamic Shape Optimization of Helicopter Rotor Blades

**Key Words:**

Optimization; Helicopter; Hover; Rotor blade; Aerodynamics.

**Summary:**

This study proposes an optimization process of helicopter rotor blades in hover for aerodynamic performance enhancements. The Caradonna-Tung rotor is used as a baseline to start the optimization, ending up with new geometry with enhanced characteristics. The study starts with searching for optimal blade airfoil shape using the adjoint method, hence this optimal shape is used to redesign the baseline blade with a genetic algorithm code. This study considers helicopter rotor in hover only, so that the hovering required power is chosen as the objective function which is formulated in figure of merit parameter, in addition to the main rotor total thrust as a second objective. Verification of this process is performed with a steady Reynolds-averaged Navier-stokes CFD simulation by comparing the two blades and checking the optimization process accuracy. Optimal blade should show the required improvements comparing to the baseline.

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# **Dedication**

I would like to dedicate my thesis to my beloved family.

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# Nomenclature

|              |                                   |
|--------------|-----------------------------------|
| $a$          | speed of sound                    |
| $C$          | main rotor blade chord            |
| $c_d$        | sectional coefficient of drag     |
| $C_p$        | power coefficient                 |
| $C_{pi}$     | induced power coefficient         |
| $cl$         | sectional lift coefficient        |
| $C_T$        | main rotor thrust coefficient     |
| $c_T$        | sectional coefficient of thrust   |
| $cl/cd$      | lift to drag coefficients ratio   |
| $D$          | drag force                        |
| DL           | rotor disk loading                |
| $dA$         | rotor annulus area                |
| $dC_{pi}$    | annulus induced power coefficient |
| $dr$         | elemental annulus blade radius    |
| $dT$         | annulus thrust force              |
| $f$          | tip loss factor correction        |
| $F$          | Prandtle's Tip Loss Factor        |
| $FM$         | figure of Merit                   |
| $F_x$        | force in x direction              |
| $F_z$        | force in z direction              |
| $i$          | induced                           |
| $j$          | waypoint index                    |
| $L$          | lift force                        |
| $M$          | Mach number                       |
| $M_{tip}$    | rotor tip Mach number             |
| $N_b$        | number of blades                  |
| $p$          | air static pressure               |
| $P$          | rotor power                       |
| PL           | rotor power loading               |
| $Q$          | rotor torque                      |
| $r$          | nondimensional radial distance    |
| $r_o$        | blade root cutout                 |
| $R$          | rotor blade radius                |
| $Re$         | Reynolds number                   |
| $T$          | air temperature                   |
| $U$          | total flow velocity               |
| $u$          | velocity component in x direction |
| $v$          | velocity component in y direction |
| $v_i$        | induced velocity                  |
| $V_c$        | climb velocity                    |
| $w$          | velocity component in z direction |
| $\mathbf{w}$ | flow field                        |
| $x, y, z$    | cartesian coordinates             |

## Greek

|                             |                            |
|-----------------------------|----------------------------|
| $\alpha$                    | sectional angle of attack  |
| $\alpha_{opt}$              | optimum angle of attack    |
| $\alpha_o$                  | zero lift angle of attack  |
| $\delta\mathcal{F}$         | airfoil shape change       |
| $\eta$                      | rotor efficiency factor    |
| $\lambda_c$                 | climb inflow ratio         |
| $\lambda_i$                 | induced inflow ratio       |
| $\lambda_{tip}$             | tip inflow ratio           |
| $v$                         | flow induced velocity      |
| $\rho$                      | air absolute density       |
| $\Omega$                    | blade rotational speed     |
| $\psi$                      | arbitrary multiplier       |
| $\lambda$                   | rotor inflow ratio         |
| $\sigma$                    | rotor solidity ratio       |
| $\rho$                      | fluid density              |
| $\sigma_{e \text{ Thrust}}$ | thrust equivalent solidity |
| $\sigma_{e \text{ Power}}$  | power equivalent solidity  |
| $\tau$                      | shear stress               |
| $\Theta$                    | blade pitch angle          |

## Abbreviations

|       |                                              |
|-------|----------------------------------------------|
| AI    | autorotation index                           |
| AoA   | angle of attack                              |
| BEMT  | blade element momentum theory                |
| BEM   | blade element theory                         |
| BVI   | blade vortex interaction                     |
| CFD   | computational fluid dynamics                 |
| CT    | Caradonna-Tung rotor blade                   |
| CST   | Class Function/Shape Function Transformation |
| HOST  | Helicopter Overall Simulation Tool           |
| ONERA | French Aeronautics and Space Research Center |
| MOGA  | multi objective genetic algorithm            |
| NACA  | National Advisory Committee for Aeronautics  |
| rpm   | revolution per minute                        |
| SBO   | Surrogate Based Optimization                 |
| 2-D   | two-dimensional                              |
| 3-D   | three-dimensional                            |

# Abstract

The aerodynamic shape design of a helicopter rotor is a challenging problem that is required for designing a rotor disk with high efficiency. This work proposes a CFD validated process to find the optimal blade configuration of a helicopter blade in hover. The adjoint method is used to find the optimal shape of the blade sectional airfoil when NACA 0012 is used as a baseline airfoil to start the optimization process. Objective function of airfoil optimization is chosen to be lift to drag coefficients ratio that showed a 17% total increase. A noticeable enhancement in blade performance is detected by an increase in figure of merit by 9.8 % due to new airfoil geometry only. Multi-objective optimization is carried out on the Caradonna-Tung rotor with figure of merit and coefficient of thrust as objective functions. Coefficient of thrust is included in this study to limit the reduction of total thrust due to figure of merit enhancements. The multi-objective genetic algorithm (MOGA) optimization technique is applied with the equivalent thrust solidity ratio as a physical constraint, and blade root chord, tip chord, point of taper initiation, twist distribution as design parameters in addition to the airfoil shape. The aerodynamic performance calculations are performed using the corrected blade element momentum theory (BEMT) that matches the wind-tunnel experimental data of the baseline rotor with 4% maximum error. Final results of the optimal blade is compared to the baseline (CT) and showed objective function increase of 17.7% with acceptable reduction in blade tip losses. In order to study the sensitivity of the maximum twist angle on the other design parameters, finding the optimal values of the design parameters process is divided into two main steps: planform geometry enhancement and then full blade geometry optimization. Inflow ratio – at each step – shows a more uniform spanwise distribution comparing to it in the previous step. A RANS CFD-Based simulation is used to evaluate both the baseline Caradonna-Tung and the optimal blade aerodynamic characteristics with an ideal gas  $k-\omega$  SST turbulence model using FLUENT's solver. Results show a great enhancement in the inflow ratio and blade tip vortices of the optimal blade. Simulation model is verified by comparing results with experimental results in order to use the same setup in optimal blade simulation. This optimization method can be used to achieve satisfactory results with less computational power comparing to high-fidelity CFD based optimization approaches.