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

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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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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I also would like to express my wholehearted thanks to my beloved family for their endless support, they provided me throughout my entire life to have a bright carrier and particularly through pursuing my master degree.

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
Vc	climb velocity
w	velocity component in z direction
$\mathcal{W}$	flow field
x, y, z	cartesian coordinates

Greek

α	sectional angle of attack
α_{opt}	optimum angle of attack
α_o	zero lift angle of attack
$\delta\mathcal{F}$	airfoil shape change
η	rotor efficiency factor
λ_c	climb inflow ratio
λ_i	induced inflow ratio
λ_{tip}	tip inflow ratio
υ	flow induced velocity
ρ	air absolute density
Ω	blade rotational speed
ψ	arbitrary multiplier
λ	rotor inflow ratio
σ	rotor solidity ratio
ρ	fluid density
$\sigma_{e\ Thrust`}$	thrust equivalent solidity
$\sigma_{e\ Power}$	power equivalent solidity
τ	shear stress
Θ	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-ω 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.