BLADE SHAPE OPTIMIZATION OF AIRCRAFT PROPELLER USING SPACE MAPPING SURROGATES

By

Eng. Usama Toson Fouad Toman

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
Engineering Mathematics

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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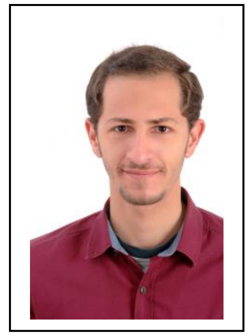

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Title of Thesis:

Blade Shape Optimization of Aircraft Propeller Using Space Mapping Surrogates

Key Words:

Propeller design optimization, blade element method, computational fluid dynamics, space mapping, kriging, surrogate model

Summary:

The aim of the present study is to perform a propeller blade shape optimization for maximum aerodynamic efficiency with a minimal number of high-fidelity model evaluations. A space mapping algorithm is utilized to link two of the most common propeller analysis models: the classical blade element momentum theory to be the coarse model; and the high-fidelity computational fluid dynamics (CFD) tool as the fine model. The optimum design is obtained after few iterations with only 56 CFD simulations. Further, an optimization method based on design of experiments and kriging response surface is used to validate the results and compare the computational efficiency of the two techniques. Finally, the shape of the blade cross-sectional airfoil is optimized to gain an additional improvement of 1.75% in the overall propeller efficiency.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Usama Toson Fouad Toman Date: 10/7/2018

Signature:

Dedication

Every challenging work needs self-efforts as well as guidance and support of persons who are very close to our heart.

I dedicate my humble effort to

- My sweet and loving '*Mother & Father'* who taught me to believe and trust in Allah and whose affection, love, encouragement and prays of day and night make me able to achieve such success.
- My beloved '*wife'*. Thank you for your advice, faith, patience and understanding.
- My supervisor '*Dr. Ahmed AbdelSamea*' without whom, literally, this work would have never been accomplished.
- *Myself*. Good work, Usama. You are great!

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Nomenclature

a	Axial induction factor
a'	Angular induction factor
A	Propeller disc area
A_e	Blade element area
B	Number of blades
c	Chord length
C_L	Lift Coefficient
C_D	Drag Coefficient
C_t	Thrust Coefficient
D	Propeller diameter
F	Prandtl tip loss factor
J	Advance ratio
J_c	Jacobian of the coarse model
J_f	Jacobian of the fine model
$\dot{m}$	Mass flow rate
Ma	Mach number
n	Number of design cross sections
P	Power
P_i	Input power
Q	Propeller torque
dQ	Differential torque
r	Blade element radius
dr	Blade element width
rpm	Propeller angular speed, rev/min
R	Propeller radius
Re	Reynolds number
R_c	Coarse model response
R_f	Fine model response
R_s	Surrogate model response
T	Propeller thrust
dT	Differential thrust
U	Relative velocity or objective function
V_∞	Freestream velocity or aircraft speed
x_c	Coarse model point
x_c^*	Coarse model optimum point
x_f	Fine model point
x_f^*	Fine model optimum point
α	Angle of attack
β	Pitch angle
η	Propeller efficiency
λ	Weighting factor

μ	Air dynamic viscosity
ρ	Air density
σ	Local solidity
φ	Relative inflow angle
ω	Angular velocity imparted to the flow
Ω	Propeller Angular velocity, rad/sec

Abbreviations

ANN	Artificial Neural Networks
ASM	Aggressive Space Mapping
ASO	Aerodynamic Shape Optimization
BEM	Blade Element Momentum
CAD	Computer-Aided Design
CCD	Central Composite Design
CFD	Computational Fluid Dynamics
CSD	Computational Structural Dynamics
DNS	Direct Numerical Simulation
DOD	D-Optimal Design
DOE	Design of Experiments
GA	Genetic Algorithm
GEK	Gradient-Enhanced Kriging
GPE	Gradient Parameter Extraction
GSM	Generalized Space-Mapping
ISM	Implicit Space Mapping
LES	Large Eddy Simulation
LHS	Latin Hypercube Sampling
MOGA	Multi-Objective Genetic Algorithm
MPE	Multipoint Parameter Extraction
NSM	Neural Space-Mapping
NISM	Neural Inverse Space-Mapping
OLH	Optimal Latin Hypercube
OSF	Optimal Space-Filling
PE	Parameter Extraction
RANS	Reynolds-Averaged Navier-Stokes
SBO	Surrogate-Based Optimization
SM	Space-Mapping
SPE	Single-Point Parameter Extraction
UAV	Unmanned Aerial Vehicles

Abstract

The aim of the present study is to perform a propeller blade shape optimization for a maximum aerodynamic efficiency with a minimal number of high-fidelity computational fluid dynamics (CFD) model evaluations. A physics-based surrogate approach exploiting space mapping (SM) technology is employed for the design process. A space mapping algorithm is utilized, for the first time in the field of propeller design, to link two of the most common propeller analysis models: the classical, simplest, and computationally cheap blade element momentum theory to be the coarse model; and the high-fidelity but computationally expensive CFD tool as the fine model. The algorithm constructs a new "surrogate" combining the advantages of accuracy and computational cheapness of the fine and coarse models, respectively. The numerical CFD simulations are performed using the finite volume discretization of the Reynolds-Averaged Navier-Stokes (RANS) equations on an adaptive unstructured grid. Two design case studies are investigated varying the number of design parameters. In the first case, three design cross sections along the blade radius are considered: hub, mean, and tip whereas five cross sections are considered in the second case. The optimum design is obtained after few iterations with a small number of computationally expensive CFD simulations. Further, an optimization method based on design of experiments and kriging response surface is used to validate the results and compare the computational efficiency of the two techniques. The results show that SM technique is more computationally efficient.

After optimizing the overall blade shape, the shape of the cross-sectional airfoil is optimized for maximum lift to drag ratio. For this purpose, we used the Matlab optimization toolbox coupled with Xfoil software to predict the airfoil performance. PARSEC parameterization technique is used to parameterize the airfoil shape with eleven parameters. After the optimum airfoil is obtained, it is used to rebuild the optimum pre-designed blade to be then analyzed. An additional improvement of 1.75% in the overall propeller efficiency is gained.