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Aerodynamic design optimization of helicopter rotor blades including airfoil shape for forward flight

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This study proposes a process to obtain an optimal helicopter rotor blade shape including both planform and airfoil shape for helicopter aerodynamic performance in forward flight. An advanced geometry representation algorithm which uses the Class Function/Shape Function Transformation (CST) is employed to generate airfoil coordinates. With this approach, airfoil shape was considered in terms of design variables. The optimization process was constructed by integrating several programs developed by the author. Airfoil characteristics are automatically generated by an analysis tool where lift, drag, and moment coefficients of airfoil are predicted for subsonic to transonic flow and a wide range of attack angles. The design variables include twist, taper ratio, point of taper initiation, blade root chord, and coefficients of the airfoil distribution function. Aerodynamic constraints consist of limits on power available in hover and forward flight, aerodynamic requirements (lift, drag and moment coefficients) for critical flow condition occurring on rotor blades. The trim condition must be attainable in any flight condition. Objective function is chosen as a combination expression of non-dimensional required power in hover and forward flight.

1. Introduction

In contrast to fixed wing design, most rotorcraft research focuses on the design of the rotor blade to optimize performance, vibration, noise, and so on because the rotor blade performance plays an essential role in most of the disciplines in helicopter design. The aerodynamics of helicopter rotor blades is a complex discipline. Diverse regimes of flow occur on blades, such as reverse flow, subsonic flow, transonic flow, and even supersonic flow. In forward flight, a component of the free stream adds to the rotational velocity at the advancing side and subtracts from the rotational velocity at the retreating side. The blade pitch angle and blade flapping as well as the distribution of induced inflow through the rotor will all affect the blade section angle of attack (AoA) [16]. The non-uniformity of AoA over the rotor disk in conjunction with the inconstant distribution of velocity along the helicopter rotor blade makes aerodynamic analysis difficult.

There are two common approaches to blade aerodynamic performance design. First, some researchers now focus on blade shape design by selecting the point of taper initiation, root chord, taper ratio, and maximum twist which minimize hover power without degrading forward flight performance [31]. This approach usually deals with integration of several programs to build an optimization process. Michael and Francis investigated the influence of tip shape, chord, blade number, and airfoil on rotor performance. Their wind tunnel test demonstrates significant improvements that can be gained from planform tailoring and further development of airfoils, specifically for high speed rotor operation [19]. Second, some works tried to solve this problem using numerical methods. Joncheray used the vortex method, which schematizes the blade and rotational flow areas on the basis of a distribution of vortices, to calculate the air flow around a rotor in hover [13]. Pape and Beaunier created an aerodynamic optimization for helicopter rotor blade shape in hover based on the coupling of an optimizer with a three-dimensional Navier–Stokes solver [22]. Morris and Allen developed a generic computational fluid dynamics (CFD) based aerodynamic optimization tool for helicopter rotor blades in hover [21]. Gunther Wilke performed a methodological setup of variable fidelity framework for the aerodynamic optimization of helicopter rotor blades and demonstrated its capabilities for a single and multi-objective test case [32]. M. Imiela and G. Wilke investigated an optimization using a multi-fidelity approach with multiple design parameters on twist, chord, sweep, and anhedral

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Nomenclature

$A_0, \ldots, A_4$	CST coefficients	P_f	required powers in forward flight
C_d, C_l, C_m	drag, lift, moment coefficient	P_h	required power in hover flight
M	Mach number	$P_{f_{ref}}$	reference values in forward flight
M_{DD_0}	drag–divergence Mach number at zero lift	$P_{h_{ref}}$	reference values in hover flight

[12]. M. Imiela created an optimization framework for helicopter rotors based on high-fidelity coupled CFD/CSM analysis [11]. The optimization framework was first applied to various optimization problems in hover starting with the easy task of optimizing the twist rate for the 7A model rotor. The last optimization in hover involved all design parameters, namely twist, chord, sweep, anhedral, transition point of two different airfoil, starting point of the blade tip showing its superiority over simpler optimization problems with respect to the achieved improvement [11]. These CFD methods are reasonable for the hover case but very time consuming. Moreover, application of the CFD method to the flow field passing the blade in forward flight is very complex. Therefore, the CFD method is not suitable for the preliminary design phase where the need for quick estimation and considering of all factors including airfoil are required.

The airfoil shape which significantly affects the performance of helicopter rotor blades is usually considered as a separate problem. Hassan et al. developed a procedure based on the coupled three-dimensional direct solutions to the full potential equation and two-dimensional inverse solution to an auxiliary equation for the design of airfoil sections for helicopter rotor blades [9]. Bousman examined the relationship between global performance of a typical helicopter and the airfoil environment [4]. McCroskey attempted to extract as much useful quantitative information as possible from critical examination and correlations of existing data obtained from over 40 wind tunnel tests [18]. Therefore, this method is not applicable to a large number of new generations of airfoil shapes. Marilyn J. Smith [24] evaluated computational fluid dynamics (CFD) codes such as OVERFLOW [6], FUN2D [1], CFL3D [23], Cobalt LLC [25], and TURNS [27] to determine 2D airfoil characteristics. With the advancement of computer technology, E.A. Mayda and C.P. van Dam developed a CFD-based methodology that automates the generation of 2D airfoil performance tables [17]. The method employs ARC2D code, which controls a 2D Reynolds-Averaged Navier–Stokes (RANS) flow solver. The method was shown to perform well for the largely “hands-off” generation of C81 tables, for use mainly in comprehensive rotorcraft analysis codes. Nevertheless, the state of the art of rotorcraft studies is not only for analysis but also for design. The method is a very expensive approach for rotorcraft analysis and design purposes where designers aim to compromise on many factors (design variables) to construct a certain objective.

The lack of less expensive analysis methods has been blocking multi-variable consideration of rotor blade design optimization. Therefore, rotor blade airfoil shapes and planforms are usually examined in isolated design optimizations. An effectively automated approach that is less expensive could contribute greatly to the rapid generation of C81 tables, to provide the ability to consider all aerodynamic aspects in rotor blade design optimization. Vu et al. have developed a tool that can rapidly and accurately compute airfoil data that are needed for rotorcraft design and analysis purposes [29].

With the aim of allowing quick estimation in the preliminary design phase, this study proposes a process to obtain an optimal helicopter rotor blade shape including both planform and airfoil shape for helicopter aerodynamic performance. In this study, a new geometry representation algorithm which uses the Class Function/Shape Function Transformation (CST) method was applied to consider airfoil shape. The advantages of this CST method are high accuracy and the use of few variables in geometry representation [15]. The effective tool for the automated generation of airfoil characteristics tables is employed in the design process. The process associates a number of commercial software packages and in-house codes that employ diverse methodologies including the Navier–Stokes equation-solving method, the high-order panel method and Euler equations solved with the fully coupled viscous–inviscid interaction (VII) method.

The design process is represented in Fig. 1. This process also includes a sizing module. After setting the size of the helicopter, the helicopter rotor blade shape optimization process is performed as the next step of the design process. Following this process, a set of initial values for design variables is chosen from the sizing module. The airfoil baseline, which is airfoil NACA0012, was chosen for the first step of the design process. Then, blade shape variables such as chord distribution, twist distribution, and airfoil point coordinates are generated. The required power for hover and forward flight is computed by the Konkuk Helicopter Design Program (KHDP), and the trim condition is checked. Airfoil analysis is performed by the automated process program. The airfoil aerodynamic characteristics are represented in C81 table format. Some other additional codes to generate airfoil coordinates, chord distribution, and twist distribution are implemented in order to build a full framework for the optimization process in ModelCenter software. ModelCenter is a powerful tool for automating and integrating design codes. Once a model has been constructed, trade studies such as parametric studies, optimization studies, and Design of Experiment (DOE) studies may be performed [20].

2. Design process

2.1. Design considerations

The power required to drive the main rotor is formed by two components: induced power and profile power (to overcome viscous losses at the rotor). The induced power and the profile power primarily influence the blade aerodynamics performance design [16]. Helicopter hover performance is expressed in terms of power loading or figure of merit (FM). A helicopter having good hover performance may have inferior performance in forward flight. The compromise between hover and forward flight leads us to express the target design value in terms of the required power in hover and forward flight.

The conventional approach to blade aerodynamics performance design fixed the airfoil shape. In general, the choice of airfoils is controlled by the need to avoid exceeding the section drag divergence Mach number on the advancing side of the rotor disk, the maximum section lift coefficients on the retreating side of the rotor disk and the zero-lift pitching moments.

The present work considers the effect of blade airfoil shape on required power. Therefore, a baseline airfoil NACA0012 was chosen as a unique airfoil for the blade to simplify the process of optimum design. The airfoil shape is represented by CST function coefficients. These coefficients are also the design variables of the examined optimization problem.

The above discussion shows that the induced and profile power can be represented as functions of twist, taper ratio, point of taper