

AERODYNAMIC OPTIMIZATION OF COAXIAL ROTOR IN HOVER AND AXIAL FLIGHT

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Abstract

The paper presents an aerodynamic optimization of a coaxial rotor system in hover and axial flight. For that purpose, a suitable theorem of calculus of variations that provides a new generic result is employed. The analysis is founded on the Blade Element-Momentum Theory, which is based on nonlinear aerodynamics and mutual (interactional) influences that are introduced by the induced downwash field of each rotor over the other. The influence of non-uniformity of the downwash distribution on the optimal design was also studied. The analysis supplies an important insight into the optimal design and efficiency of coaxial rotor systems. The formulation is consistently generic and enables the exploration of a wide range of coaxial configurations.

Nomenclature

A	Disc square = πR^2 .
c_d	Drag coefficient.
c_l	Lift coefficient.
C_P	Power coefficient (= $P / (\rho A \Omega^3 R^3)$). All parameters belong to the rotor under discussion.
C_T	Thrust coefficient (= $T / (\rho A \Omega^2 R^2)$). All parameters belong to the rotor under discussion.
h	Rotor's clearance of the coaxial system.
k	Influence coefficient.
N_b	Number of blade.
R	Disc radius.
r	Spanwise location along the blade of the rotor

	under discussion ($0 < r < R$).
r_w	Upper rotor wake radius.
T	Rotor thrust, positive upwards.
V_t	Tip speed (= ΩR).
α	Angle of attack.
γ	Numerical coefficient in the expressions for k .
ζ_R	Coaxial system rotors radius ratio.
ζ_Ω	Coaxial system angular velocities ratio.
η	Lagrange multiplier.
θ_{pitch}	Blade pitch angle.
θ_{tw}	Blade twist angle.
κ	Induced power correction coefficient.
λ_c	Nondimensional climb velocity of the coaxial system (normalized by $\Omega^U R^U$).
$\lambda_c^{(1)}$	Nondimensional "equivalent" climb velocity (normalized by ΩR of the rotor under discussion).
λ_i	Nondimensional induced velocity (normalized by ΩR of the rotor under discussion).
ρ	Air density.
Ω	Rotor angular velocity.
$()^U$	Quantity related to the upper rotor.
$()^L$	Quantity related to the lower rotor.
$()^I$	Quantity related to the inner part of the lower rotor.
$()^{LO}$	Quantity related to the outer part of the lower rotor.
$()$	Nondimensional length quantity, normalized by R .
$()$	Averaged quantity.
$()^*$	Time averaged quantity.

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Computational Investigation of Micro-scale Coaxial Rotor Aerodynamics in Hover Vinod K. Lakshminarayan,2009

Computational Investigation of Micro-scale Coaxial Rotor Aerodynamics in Hover ,2009 Computational investigation of micro scale coaxial rotor aerodynamics in hover **Performance Analysis of Coaxial Helicopter in Hover and Forward Flight** Stanrich D. Fernandes,2017 The performance of a coaxial rotor system has been analyzed by establishing a proper basis of comparison between a conventional single between a conventional single rotor and coaxial rotor An attempt rotor and coaxial rotor An attempt has also been made to better understand the complicated aerodynamic interactions associated with coaxial rotor wakes by using a free vortex methodology FVM The FVM is a Lagrangian based wake convection methodology which solves for the evolution of the vortical wake produced by the rotor blades under the influence of an external flow The extent to which the two rotors interact with each other was found to be highly dependent on the inter rotor spacing To this end parametric variations of inter rotor spacing were performed to show the effect on performance on each rotor and also as a system An attempt was made to quantify the effect of aerodynamic interference on the performance of the upper and lower rotor by comparing them to an isolated rotor It was shown that the equivalent single rotor performs better than the coaxial rotor at moderately high advance ratios while the coaxial rotor performs better in hover The inter rotor spacing profoundly affected the performance of the coaxial rotor system giving higher power requirements a lower inter rotor spacing Finally it was shown that the upper rotor becomes affected by the lower rotor in hover and while this was an expected result in hover and low advance ratios the performance of the upper rotor was also affected at higher advance ratios *Coaxial Rotor Aerodynamic Interactions and Effect on Performance* Belen Bowman,2025 In recent years the demand for small multi rotor vertical takeoff and landing VTOL vehicles for urban air mobility and other applications has increased Within the category of multi rotor vehicles are vehicles that incorporate coaxial rotor systems Coaxial rotors inherently provide anti torque while simultaneously providing thrust This eliminates the need for a tail rotor as is used in conventional helicopters requiring less power than an equivalent single rotor in hover Coaxial rotor vehicles are also more stable in flight and more maneuverable compared to conventional helicopters Improving the performance of coaxial rotors in various flight conditions can increase the vehicle payload speed and or range capabilities

thus expanding the usefulness and applications where coaxial rotors are appropriate Improved performance has been important for large scale vehicles for decades and is now also critical for small electric VTOL vehicles such as lower passenger capacity vehicles for short commutes and package delivery vehicles which are designed as multi rotor vehicles Through further investigation and understanding of the environment created by coaxial rotor flows and changing designs to certain rotor parameters such as the rotor separation distance and the differential RPM coaxial rotor efficiency may be increased Existing publications related to the topic of coaxial rotor performance have investigated the effects of coaxial rotor separation but there are inconsistencies in the results Some have observed no performance gain beyond an axial separation distance $z/D = 0.05$ while others found no change in the rotor performance when the axial separation distance was greater than $z/D = 0.15$ Among the discussions of coaxial rotor performance are studies on wake swirl recovery Energy from the rotor rotation is transferred to the wake by energy conservation Some of the energy is transferred as rotational energy and induces swirl in the wake The studies on swirl recovery have not included differential speed but have produced differing conclusions as some have determined that the reduction of induced power of a counter rotating coaxial rotor is due to a recovery of energy from the wake while another argument is that the improvement in performance is not so much from swirl recovery but from interference effects on the inflow Further investigation of the flow of a coaxial rotor including the inflow of the rotors and the wake swirl at different axial separation distances and rotor differential speeds could provide physical insight to ultimately obtain rotor performance improvement The following is the work completed to computationally study the effect of rotor inflow and wake swirl on the performance of coaxial rotors in hover using a blade element model approach in STAR CCM which is a commercially available multidisciplinary analysis platform The environment of a coaxial rotor flow and the interactions of the rotors can be studied in detail using computational fluid dynamics CFD methods The computational approach was verified by correlating results against experimental test data The verification was conducted with an isolated rotor in hover and a coaxial rotor in hover using experimental data In addition experimental testing conducted in the Coaxial Acoustics Test System at The Pennsylvania State University was used to measure the effect of rotor spacing and differential rotor speed on the performance of the rotor All configurations provided thrust and torque measurements for the individual rotors The performance predictions obtained using STAR CCM were then compared to the experimental results and the results agreed that at RPM ratios lower than 1 where the upper rotor RPM was lower than that of the lower rotor the performance of the coaxial rotor improved between 1% and 3% for the range of RPM ratios tested Both the separation distance and RPM ratio changes produced changes in the flow of the rotors which were characterized and compared to the flow through a single two bladed rotor While the upper rotor experienced little effect from the lower rotor beyond a separation distance of $z/R = 0.5$ the lower rotor experienced an increased effect of the upper rotor with increasing separation distance on sections of the blade inboard of about 60% of the radius Over the total range of the separation distances the

upper rotor experienced increases in the angle of attack of about 2-3 over the span of the blade compared to a single rotor. The angle of attack of the lower rotor decreased by more than 5 near the root of the blade over the range of separation distances compared to a single rotor. The changes in the angle of attack changed the efficiency C_l/C_d of the blade sections and subsequently the blade and the rotor. For this rotor, small decreases in the angle of attack slightly increased the efficiency of the blade sections and greater decreases in the angle of attack as for the lower rotor decreased the efficiency of the blade sections. The thrust torque and power varied with the changes in separation distance and RPM ratio. To compare performance, observing the thrust to torque ratio indicated that the performance for the coaxial rotor with separation distance $z/R = 0.2$ improved by about 2% at an RPM ratio of 1.2, but observing the thrust to power ratio, power loading indicated that the performance improved by almost 8% at an RPM ratio of 0.8. The power required by the rotor is the multiplication of the torque and the rotational speed and in the case of varying rotational speeds, using the power to compare the performance incorporates the effect of the rotor rotational speed. Differential RPM between the rotors of a coaxial configuration was investigated. The effect of the upper rotor wake on the lower rotor due to variations in rotor differences such as RPM or rotor separation has proven to affect the performance of the coaxial rotor system. Changes in the separation distance and other design parameters such as the airfoil chord and twist distributions of the upper and lower rotors could be optimized together with the rotor RPM differential to produce a coaxial rotor system that maximizes efficiency over a range of flight conditions.

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Aerodynamic Optimization of Helicopter Rotor Blades Using Variable Fidelity Methods Gunther Andreas Wilke, 2017

An Integrated Optimum Design Approach for High Speed Prop Rotors National Aeronautics and Space

Administration (NASA), 2018-07-06. The objective is to develop an optimization procedure for high speed and civil tilt rotors by coupling all of the necessary disciplines within a closed loop optimization procedure. Both simplified and comprehensive analysis codes are used for the aerodynamic analyses. The structural properties are calculated using in-house developed algorithms for both isotropic and composite box beam sections. There are four major objectives of this study:

1. Aerodynamic optimization: The effects of blade aerodynamic characteristics on cruise and hover performance of prop rotor aircraft are investigated using the classical blade element momentum approach with corrections for the high lift capability of rotor propellers.
2. Coupled aerodynamic structures optimization: A multilevel hybrid optimization technique is developed for the design of prop rotor aircraft. The design problem is decomposed into a level for improved aerodynamics with continuous design variables and a level with discrete variables to investigate composite tailoring. The aerodynamic analysis is based on that developed in objective 1 and the structural analysis is performed using an in-house code which models a composite box beam. The results are compared to both a reference rotor and the optimum rotor found in the purely aerodynamic formulation.
3. Multipoint optimization: The multilevel optimization procedure of objective 2 is extended to a multipoint design problem.

Hover cruise and take off are the three flight conditions simultaneously maximized 4 Coupled rotor wing optimization Using the comprehensive rotary wing code CAMRAD an optimization procedure is developed for the coupled rotor wing performance in high speed tilt rotor aircraft The developed procedure contains design variables which define the rotor and wing planforms Chattopadhyay Aditi and McCarthy Thomas R Unspecified Center

A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research National Aeronautics and Space Administration (NASA),2018-06-29 The recent appearance of the Kamov Ka 50 helicopter and the application of coaxial rotors to unmanned aerial vehicles have renewed international interest in the coaxial rotor configuration This report addresses the aerodynamic issues peculiar to coaxial rotors by surveying American Russian Japanese British and German research Herein coaxial rotors refers to helicopter not propeller rotors The intermeshing rotor system was not investigated Issues addressed are separation distance load sharing between rotors wake structure solidity effects swirl recovery and the effects of having no tail rotor A general summary of the coaxial rotor configuration explores the configuration s advantages and applications Coleman Colin P Ames Research Center RTOP 522 31 12 RTOP 522 41 22

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Rotary-Wing Aerodynamics W. Z. Stepniewski,2013-04-22 DIVClear concise text covers aerodynamic phenomena of the rotor and offers guidelines for helicopter performance evaluation Originally prepared for NASA Prefaces New Indexes 10 black and white photos 537 figures div

Integrated Aerodynamic/Dynamic Optimization of Helicopter Rotor Blades National Aeronautics and Space Adm Nasa,2018-12-29 An integrated aerodynamic dynamic optimization procedure is used to minimize blade weight and 4 per rev vertical hub shear for a rotor blade in forward flight The coupling of aerodynamics and dynamics is accomplished through the inclusion of airloads which vary with the design variables during the optimization process Both single and multiple objective functions are used in the optimization formulation The Global Criteria Approach is used to formulate the multiple objective optimization and results are compared with those obtained by using single objective function formulations Constraints are imposed on natural frequencies autorotational inertia and centrifugal stress The program CAMRAD is used for the blade aerodynamic and dynamic analyses and the program CONMIN is used for the optimization Since the spanwise and the azimuthal variations of loading are responsible for most rotor vibration and noise the vertical airload distributions on the blade before and after optimization are compared The total power required by the rotor to produce the same amount of thrust for a given area is also calculated before and after optimization Results indicate that integrated optimization can significantly reduce the blade

weight the hub shear and the amplitude of the vertical airload distributions on the blade and the total power required by the rotor Chattopadhyay Aditi and Walsh Joanne L and Riley Michael F Langley Research Center NASA TM 101553 NAS 1 15 101553 AIAA PAPER 89 1269 RTOP 505 61 51 10 **Modeling and Simulation of Coaxial Helicopter Rotor**

Aerodynamics Murat Gecgel, Old Dominion University. Department of Aerospace Engineering, 2009 Optimization of a Wing Supporting a Coaxial Rotor for Multiple Flight Conditions Tadd Yeager, 2021 Rotor powered drones continue to grow in popularity in private and government sectors The use of these drones in challenging environments and in high stakes applications calls for a certain level of robustness and redundancy Often these drones are equipped with sets of paired coaxial rotors which not only improve the performance of the vehicle but also ensure that a failure of one motor does not constitute the failure of the whole vehicle Some applications such as extraterrestrial exploration which use these coaxial rotors can benefit from a wing shaped rotor arm to reduce drag and increase lift extending mission lifetime This work explores the design of one such coaxial rotor wing system using computational fluid dynamics to assess the system performance in a pair of flight conditions Various parameters of the wing design are adjusted to ascertain the optimal configuration to satisfy various performance criteria

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Table of Contents Aerodynamic Optimization Of Coaxial Rotor In Hover Icas

1. Understanding the eBook Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - The Rise of Digital Reading Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Advantages of eBooks Over Traditional Books
2. Identifying Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - User-Friendly Interface
4. Exploring eBook Recommendations from Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Personalized Recommendations

- Aerodynamic Optimization Of Coaxial Rotor In Hover Icas User Reviews and Ratings
- Aerodynamic Optimization Of Coaxial Rotor In Hover Icas and Bestseller Lists
- 5. Accessing Aerodynamic Optimization Of Coaxial Rotor In Hover Icas Free and Paid eBooks
 - Aerodynamic Optimization Of Coaxial Rotor In Hover Icas Public Domain eBooks
 - Aerodynamic Optimization Of Coaxial Rotor In Hover Icas eBook Subscription Services
 - Aerodynamic Optimization Of Coaxial Rotor In Hover Icas Budget-Friendly Options
- 6. Navigating Aerodynamic Optimization Of Coaxial Rotor In Hover Icas eBook Formats
 - ePub, PDF, MOBI, and More
 - Aerodynamic Optimization Of Coaxial Rotor In Hover Icas Compatibility with Devices
 - Aerodynamic Optimization Of Coaxial Rotor In Hover Icas Enhanced eBook Features
- 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Highlighting and Note-Taking Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Interactive Elements Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
- 8. Staying Engaged with Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
- 9. Balancing eBooks and Physical Books Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
- 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
- 11. Cultivating a Reading Routine Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Setting Reading Goals Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Aerodynamic Optimization Of Coaxial Rotor In Hover Icas
 - Fact-Checking eBook Content of Aerodynamic Optimization Of Coaxial Rotor In Hover Icas

- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
- 14. Embracing eBook Trends
 - Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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