

Notes on Numerical Fluid Mechanics  
and Multidisciplinary Design 142

Andreas Dillmann  
Gerd Heller  
Ewald Krämer  
Claus Wagner  
Cameron Tropea  
Suad Jakirlić *Editors*

# New Results in Numerical and Experimental Fluid Mechanics XII

Contributions to the 21st STAB/DGLR  
Symposium, Darmstadt, Germany, 2018

# **Notes on Numerical Fluid Mechanics and Multidisciplinary Design**

Volume 142

## **Founding Editor**

Ernst Heinrich Hirschel, Zorneding, Germany

## **Series Editors**

Wolfgang Schröder, Aerodynamisches Institut, RWTH Aachen, Aachen, Germany

Bendiks Jan Boersma, Delft University of Technology, Delft, The Netherlands

Kozo Fujii, Institute of Space & Astronautical Science (ISAS), Sagamihara,  
Kanagawa, Japan

Werner Haase, Hohenbrunn, Germany

Michael A. Leschziner, Department of Aeronautics, Imperial College, London, UK

Jacques Periaux, Paris, France

Sergio Pirozzoli, Dept. Mechanical and Aerospace Eng., University of Rome  
'La Sapienza', Roma, Italy

Arthur Rizzi, Department of Aeronautics, KTH Royal Institute of Technology,  
Stockholm, Sweden

Bernard Roux, Ecole Supérieure d'Ingénieurs de Marseille, Marseille CX 20,  
France

Yurii I. Shokin, Siberian Branch of the Russian Academy of Sciences, Novosibirsk,  
Russia

Notes on Numerical Fluid Mechanics and Multidisciplinary Design publishes state-of-art methods (including high performance methods) for numerical fluid mechanics, numerical simulation and multidisciplinary design optimization. The series includes proceedings of specialized conferences and workshops, as well as relevant project reports and monographs.

More information about this series at <http://www.springer.com/series/4629>

Andreas Dillmann · Gerd Heller ·  
Ewald Krämer · Claus Wagner ·  
Cameron Tropea · Suad Jakirlić  
Editors

# New Results in Numerical and Experimental Fluid Mechanics XII

Contributions to the 21st STAB/DGLR  
Symposium, Darmstadt, Germany, 2018

### *Editors*

Andreas Dillmann  
Deutsches Zentrum für Luft- und Raumfahrt  
Institut für Aerodynamik  
und Strömungstechnik  
Göttingen, Niedersachsen, Germany

Ewald Krämer  
Institut für Aerodynamik und Gasdynamik  
Universität Stuttgart  
Stuttgart, Baden-Württemberg, Germany

Cameron Tropea  
Fachgebiet Strömungslehre  
und Aerodynamik  
Technische Universität Darmstadt  
Darmstadt, Hessen, Germany

Gerd Heller  
Airbus Operations GmbH  
Bremen, Bremen, Germany

Claus Wagner  
Deutsches Zentrum für Luft- und Raumfahrt  
Institut für Aerodynamik  
und Strömungstechnik  
Göttingen, Niedersachsen, Germany

Suad Jakirlić  
Fachgebiet Strömungslehre  
und Aerodynamik  
Technische Universität Darmstadt  
Darmstadt, Hessen, Germany

ISSN 1612-2909

ISSN 1860-0824 (electronic)

Notes on Numerical Fluid Mechanics and Multidisciplinary Design

ISBN 978-3-030-25252-6

ISBN 978-3-030-25253-3 (eBook)

<https://doi.org/10.1007/978-3-030-25253-3>

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Foreword

This volume contains the papers presented at the 21st STAB/DGLR Symposium held in Darmstadt, Germany (November 6–7, 2018) organized by the Institute for Fluid Mechanics and Aerodynamics at the Technische Universität Darmstadt. STAB is the German Aerospace Aerodynamics Association (Deutsche Strömungsmechanische Arbeitsgemeinschaft) founded towards the end of the 1970s, and DGLR is the German Society for Aeronautics and Astronautics (Deutsche Gesellschaft für Luft- und Raumfahrt - Lilienthal Oberth e.V.).

The mission of STAB is to foster aerodynamics research and its appreciation in Germany. This is accomplished by creating forums for scientific discussions and by disseminating most recent research results, thereby enhancing scientific progress and avoiding unnecessary duplication in research work.

STAB brings together German scientists and engineers from universities, research establishments and industry. They present research and project work in numerical and experimental fluid mechanics as well as aerodynamics for diverse fields, such as aeronautics, space, ground transportation, wind turbines and other applications. This format also offers an excellent opportunity for exchange about numerous common research activities sponsored by different funding agencies.

Since 1986 the symposium takes place every two years at different locations in Germany, all having an affinity to fluid mechanics and aerodynamics.

In addition STAB Workshops are held regularly at DLR (Deutsches Zentrum für Luft- und Raumfahrt) in Göttingen in the intermediate years.

Both, STAB symposia and workshops provide excellent forums where new research activities can be presented, often resulting in new jointly organized research and technology projects.

In this volume symposium contributions are published for the twelfth time, following a thorough peer review.

The review board, comprising also the programme committee, consisted of P. Bahavar (Göttingen), C. Bauer (Göttingen), J. Bell (Göttingen), T. Berkefeld (Göttingen), I. Bolgar (Neubiberg), A. Botelho e Souza (Braunschweig), M. Braune (Göttingen), J. Breitenbach (Darmstadt), C. Breitsamter (München), C. Brückner (Göttingen), A. Buhr (Göttingen), O. Burghardt (Kaiserslautern), M. Burnazzi

(Göttingen), M. Costantini (Göttingen), A. Dannhauer (Göttingen), J. Delfs (Braunschweig), R. du Puits (Ilmenau), K. Ehrenfried (Göttingen), R. Ewert (Braunschweig), B. Faßmann (Braunschweig), M. Fehrs (Göttingen), U. Fey (Göttingen), H. Foysi (Siegen), A. Gardner (Göttingen), D. Gatti (Karlsruhe), N. Gauger (Kaiserslautern), R. Geisler (Göttingen), C. Grabe (Göttingen), A. Guissart (Darmstadt), V. Hannemann (Göttingen), F. Heckmeier (München), M. Hehner (Karlsruhe), A. Heider (Göttingen), S. Hein (Göttingen), S. Helm (Göttingen), A. Henning (Göttingen), S. Herbst (Neubiberg), N. Herzog (Taufkirchen), S. Herzog (Göttingen), S. Hitzel (Manching), A. Hövelmann (Manching), A. Hübner (Braunschweig), D. Iglesias (Gilching), C. Ilic (Braunschweig), S. Jakirlić (Darmstadt), C. Jessing (Stuttgart), C. Kästner (Ilmenau), K. Kaufmann (Göttingen), A. Kellersmann (Braunschweig), M. Keßler (Stuttgart), T. Kilian (Braunschweig), J. Kissing (Darmstadt), D. Klatt (Saint-Louis), C. Klein (Göttingen), J. Klinner (Köln), M. Kloker (Stuttgart), T. Knopp (Göttingen), R. Konrath (Göttingen), M. Konstantinov (Göttingen), M. Kotsonis (Delft), U. Krause (Bremen), A. Krumbein (Göttingen), B. Krumbein (Darmstadt), A. Kümmel (München), P. Kunze (Braunschweig), P. Lange (Göttingen), R. Lechner (Otterfing), A. Lösch (Ilmenau), T. Lutz (Stuttgart), R. Maduta (Darmstadt), J. Martinez Schramm (Göttingen), E. Mäteling (Aachen), A. Merle (Braunschweig), B. Michels (Braunschweig), A. Mielke (Saint-Louis), M. Mommert (Göttingen), M. Müller (Göttingen), M. M. Müller (Göttingen), J. Nitzsche (Göttingen), E. Öngüner (Göttingen), J. Pflüger (München), S. Pfnür (München), P. Pözlbauer (München), A. Probst (Göttingen), D. Puckert (Stuttgart), D. Ramaswamy (Aachen), M. Reder (Karlsruhe), A. Reeh (Taufkirchen), L. Reimer (Braunschweig), M. Rein (Göttingen), K. Richter (Göttingen), S. Risius (Göttingen), U. Rist (Stuttgart), M. Ritter (Göttingen), M. Rütten (Göttingen), S. Scharnowski (Neubiberg), J. B. Schmidt (Darmstadt), O. Schmidt (San Diego), A. Schreyer (Aachen), A. Schröder (Göttingen), E. Schüle (Göttingen), T. Schütz (München), T. Schwarz (Braunschweig), B. Selent (Stuttgart), J. Serpieri (Delft), L. Siegel (Göttingen), C. Stanger (Stuttgart), A. Stroh (Karlsruhe), M. Stuhlpfarrer (München), G. Subbian, (Braunschweig), A. Suryadi (Braunschweig), E. Tangermann (Neubiberg), J. Ullah (Stuttgart), N. van Hinsberg (Göttingen), M. Vieweg (Köln), C. Voß (Göttingen), A. Waldmann (Stuttgart), K. Weinman (Göttingen), M. Werner (Göttingen), A. Westhoff (Göttingen), T. Wetzel (Göttingen), F. Wienke (Göttingen), H. Wilhelmi (Göttingen), G. Wilke (Braunschweig), A. Winkler (Manching), M. Winter (München), Y. Wu (Stuttgart), S. Yadala (Poitiers), Y. Zhang (Darmstadt).

Nevertheless, the authors sign responsible for the contents of their contributions.

The editors are grateful to Prof. Dr. W. Schröder as the General Editor of the “Notes on Numerical Fluid Mechanics and Multidisciplinary Design” series and to the Springer publishing house for the opportunity to publish the results of the symposium.

February 2019

A. Dillmann  
G. Heller  
E. Krämer  
C. Wagner  
C. Tropea  
S. Jakirlić



# Contents

**Airplane Aerodynamics/Propulsion Integration**

**Implementation of a Method to Determine Aerodynamic  
Propeller-Wing Interaction . . . . . 3**  
Nikolai Herzog and Andreas Reeh

**Unsteady Wake and Tailplane Loads of the Common Research  
Model in Low Speed Stall . . . . . 14**  
Andreas Waldmann, Robert Konrath, Thorsten Lutz, and Ewald Krämer

**Optimization**

**Accurate Gradient Computations for Shape Optimization  
via Discrete Adjoints in CFD-Related Multiphysics Problems . . . . . 27**  
Ole Burghardt and Nicolas R. Gauger

**Cybermatrix: A Novel Approach to Computationally  
and Collaboration Intensive Multidisciplinary Optimization  
for Transport Aircraft Design . . . . . 37**  
Časlav Ilić, Andrei Merle, Arno Ronzheimer, Mohammad Abu-Zurayk,  
Jonas Jepsen, Martin Leitner, Matthias Schulze, Andreas Schuster,  
Michael Petsch, and Sebastian Gottfried

**Global Aerodynamic Design Optimization via Primal-Dual  
Aggregation Method . . . . . 48**  
Emre Özkaya and Nicolas R. Gauger

**Turbulence Research and Turbulence Modeling**

**Validation of a New Near-Wall Reynolds Stress Model  
for Aeronautical Applications . . . . . 61**  
Ana Carolina Botelho e Souza and Rolf Radespiel

<b>Development of Artificial Neural Networks with Integrated Conditional Random Fields Capable of Predicting Non-linear Dynamics of the Flow Around Cylinders . . . . .</b>	<b>71</b>
Sebastian Herzog and Claus Wagner	
<b>Modification of the SSG/LRR-<math>\omega</math> RSM for Turbulent Boundary Layers at Adverse Pressure Gradient with Separation Using the New DLR VicToria Experiment . . . . .</b>	<b>80</b>
Tobias Knopp, Matteo Novara, Daniel Schanz, Reinhard Geisler, Florian Philipp, Michael Schroll, Christian Willert, and Andreas Schröder	
<b>A Scale-Resolving Elliptic-Relaxation-Based Eddy-Viscosity Model: Development and Validation . . . . .</b>	<b>90</b>
Benjamin Krumbein, Robert Maduta, Suad Jakirlić, and Cameron Tropea	
<b>Development of a Generalized K-<math>\omega</math> Two-Equation Turbulence Model . . .</b>	<b>101</b>
Florian R. Menter, Alexey Matyushenko, and Richard Lechner	
<b>Turbulent Inflow Generation by Resolvent Mode Forcing . . . . .</b>	<b>110</b>
Björn Selent, Christoph Wenzel, Ulrich Rist, and Oliver T. Schmidt	
<b>Assessment and Modification of the <math>\gamma - Re_\theta</math> Transition Model Behavior Outside the Boundary Layer . . . . .</b>	<b>120</b>
Philip Ströer, Cornelia Grabe, and Andreas Krumbein	
<b>Assessment of Extensions for an Eddy Viscosity Turbulence Model for Vortical Flows . . . . .</b>	<b>131</b>
Gokul Subbian and Rolf Radespiel	
<b>Hypersonic Aerodynamics</b>	
<b>Time Response Calibration of Ultra-fast Temperature Sensitive Paints for the Application in High Temperature Hypersonic Flows . . . .</b>	<b>143</b>
Jan Martinez Schramm and Michael Hilfer	
<b>Laminar Flow Control and Transition</b>	
<b>Surface Temperature Effects on Boundary-Layer Transition at Various Subsonic Mach Numbers and Streamwise Pressure Gradients . . . . .</b>	<b>155</b>
Marco Costantini, Steffen Risius, and Christian Klein	
<b>Experimental Investigation of the Delay of Gap- and Step-Induced Transition by Means of Suction . . . . .</b>	<b>165</b>
Benjamin Dimond, Marco Costantini, Steffen Risius, Christian Klein, and Martin Rein	

<b>Boundary Layer Suction Modeling Based on the DLR TAU-Code Effusion Mass Flux Boundary Condition</b> .....	175
Michael Fehrs	
<b>Laminar to Turbulent Transition at Unsteady Inflow Conditions: Flight Experiments Under Calm and Moderately Turbulent Conditions</b> .....	185
Amandine Guissart, Timotheus Nemitz, and Cameron Tropea	
<b>Validation Experiment on a Passive Suction Flap for Hybrid Laminar Flow Control Applications</b> .....	195
Thomas Kilian, Udo Krause, Sven Schaber, and Dimitri Neufeld	
<b>On the Role of Secondary Structures During Leading Edge Vortex Lift Off and Detachment on a Pitching and Plunging Flat Plate</b> .....	204
Johannes Kissing, Jochen Kriegseis, and Cameron Tropea	
<b>Laminar to Turbulent Transition at Unsteady Inflow Conditions: Direct Numerical Simulations with Small Scale Free-Stream Turbulence</b> .....	214
Duncan Ohno, Jonas Romblad, and Ulrich Rist	
<b>Transition Delay with Cylindrical Roughness Elements in a Laminar Water Channel</b> .....	225
Dominik K. Puckert and Ulrich Rist	
<b>Influence of Jet Spacing and Injection Pressure on Separation Control with Air-Jet Vortex Generators</b> .....	234
Deepak Prem Ramaswamy, Rasmus Hinke, and Anne-Marie Schreyer	
<b>Preliminary Study of Flow Control via Uniform Blowing on Airfoils with a Boundary Element Method</b> .....	244
Martin Reder, Alexander Stroh, and Davide Gatti	
<b>Laminar to Turbulent Transition at Unsteady Inflow Conditions: Wind Tunnel Measurements at Oscillating Inflow Angle</b> .....	254
Jonas Romblad, Duncan Ohno, Werner Würz, and Ewald Krämer	
<b>Investigations on a Mechanism to Induce Free-Stream Turbulence in a Water Channel by Controlled Injection of Air Bubbles</b> .....	265
Martin Siring, Dominik K. Puckert, and Ulrich Rist	
<b>Boundary Layer Stability with Embedded Rotating Cylindrical Roughness Element</b> .....	274
Yongxiang Wu and Ulrich Rist	

**High-Agility Configuration**

**Application of Lifetime-Based Pressure-Sensitive Paint  
for Transonic Tests on a Generic Delta Wing Planform . . . . . 287**

Ulrich Henne, Daisuke Yorita, and Christian Klein

**Vortex Flow Aerodynamic Challenges in the Design Space  
for Future Fighter Aircraft . . . . . 297**

Stephan M. Hitzel, Andreas Winkler, and Andreas Hövelmann

**Analysis of Vortex Flow Phenomena on Generic Delta Wing  
Planforms at Transonic Speeds . . . . . 307**

Andreas Hövelmann, Andreas Winkler, Stephan M. Hitzel, Kai Richter,  
and Michael Werner

**Magnus Effect for Finned Bodies of Revolution in Supersonic Flow . . . 317**

Alina Mielke, Daniel Klatt, and Christian Mundt

**Analysis of Vortex Flow Phenomena on Generic Delta Wing  
Planforms at Subsonic Speeds . . . . . 328**

Stefan Pfnür, Jonathan Pflüger, and Christian Breitsamter

**Computational Aerodynamic Sensitivity Studies for Generic  
Delta Wing Planforms . . . . . 338**

Andreas Schütte and Rebeca Nunes Marini

**Rotorcraft Aerodynamics**

**Dynamic Stall Computations of Double-Swept Rotor Blades . . . . . 351**

Kurt Kaufmann, Martin M. Müller, and Anthony D. Gardner

**Propeller Blade Shape Optimization with a Hybrid  
BEMT/CFD Approach . . . . . 362**

Andreas Kümmel, Marco Stuhlpfarrer, Patrick Pölzlbauer,  
and Christian Breitsamter

**Aerodynamic Analysis and Optimization of Wings and Tail  
Surfaces of a Compound Helicopter with Box Wing . . . . . 372**

Philipp Kunze and Marc Wentrup

**Unsteady Boundary Layer Transition Detection with Local  
Infrared Thermography . . . . . 382**

Christoph Mertens, C. Christian Wolf, and Anthony D. Gardner

**Aerodynamic Performance of Two eVTOL Concepts . . . . . 392**

Gunther Wilke

**Technical Flows**

<b>Experimental Analysis of the Interaction Between a Dual-Bell Nozzle with an External Flow Field Aft of a Backward-Facing Step</b> .....	405
Istvan Bolgar, Sven Scharnowski, and Christian J. Kähler	
<b>Efficient Cooling of a Generic Car Cabin by Novel Ventilation Systems</b> .....	416
Tobias Dehne and Andreas Westhoff	
<b>System Dynamics of a Single-Shaft Turbojet Engine Using Pseudo Bond Graph</b> .....	427
Jan Göing, Andreas Kellersmann, Christoph Bode, and Jens Friedrichs	
<b>Towards Aerodynamically Optimized Freight Wagons: An Experimental Study on Container Designs</b> .....	437
Emir Öngüner, Arne Henning, Uwe Fey, and Claus Wagner	
<b>Experimental and Numerical Investigation of the Interaction of Wake Vortices with a Gable Roof</b> .....	447
Anna Uhl, Sebastian Braun, and Eike Stumpf	
<b>Numerical Study of the Airflow Distribution in a Passenger Car Cabin Validated with PIV</b> .....	457
Sebastian Ullrich, Ricardo Buder, Nesrine Boughanmi, Christian Friebe, and Claus Wagner	
<b>Experimental Study on the Richardson Number Dependence of Large-Scale Flow Structures and Their Dynamics in a Miniaturised Aircraft Cabin</b> .....	468
Andreas Westhoff and Claus Wagner	
<b>Aeroelasticity and Structural Dynamics</b>	
<b>Sensitivity of Single Degree of Freedom Limit Cycle Flutter of a Laminar Airfoil and Resulting Uncertainties of the Transonic Dip</b> ....	481
Marc Braune and Anne Hebler	
<b>Towards CFD-Based Aeroelastic Analysis of NLF Wings</b> .....	491
Sebastian Helm, Michael Fehrs, and Jens Nitzsche	
<b>Experimental Investigation of the Unsteady Aerodynamics of a Pitching S809 Aerofoil at Various Reduced Frequencies and High Reynolds Numbers</b> .....	501
Nils van Hinsberg	
<b>Reduced-Order Modeling of Transonic Buffet Aerodynamics</b> .....	511
Maximilian Winter and Christian Breitsamter	

**Fluid and Thermodynamics**

**Reynolds Number Dependency of the Heat and Mass Transfer in Mixed Convective Duct Flow with Condensation at a Cooled Wall . . . .** 523

Christian Brückner, Philipp Bahavar, Andreas Westhoff, and Claus Wagner

**Experimental Investigation of Mixed Convection in Horizontal Channel Flow in Combination with Cylindrical Roughness Elements . . .** 533

Esther Mäteling, Jonathan Lemarechal, Christian Klein, Dominik K. Puckert, and Ulrich Rist

**Comparison of Two Unstable Flow States in Turbulent Mixed Convection. . . . .** 543

Konstantin A. Niehaus, Michael Mommert, Daniel Schiepel, Daniel Schmeling, and Claus Wagner

**Measurement of the Heat Flux During a Drop Impact onto a Hot Dry Solid Surface Using Infrared Thermal Imaging . . . . .** 553

J. Benedikt Schmidt, Jan Breitenbach, Ilia V. Roisman, and Cameron Tropea

**Numerical Simulation/Aerodynamics**

**Prediction Capabilities of Two Reynolds Stress Turbulence Models for a Turbulent Wake Subjected to Adverse Pressure Gradient . . . . .** 565

Marco Burnazzi, Tobias Knopp, Michale Kh. Strelets, Michael L. Shur, Andrey K. Travin, Wiebke Breitenstein, Peter Scholz, and Rolf Radespiel

**Multidisciplinary Simulation for Gust Load Alleviation Control Surface Analysis . . . . .** 576

Andreas Hübner and Lars Reimer

**Scrutinizing Conventional and Eddy-Resolving Unsteady RANS Approaches in Computing the Flow and Aeroacoustics Past a Tandem Cylinder . . . . .** 586

Felix Köhler, Robert Maduta, Benjamin Krumbein, and Suad Jakirlić

**Towards Higher-Precision Maneuver and Gust Loads Computations of Aircraft: Status of Related Features in the CFD-Based Multidisciplinary Simulation Environment FlowSimulator . . . . .** 597

Lars Reimer, Ralf Heinrich, and Markus Ritter

**Boundary Condition Based Actuator Line Model to Simulate the Aerodynamic Interactions at Wingtip Mounted Propellers. . . . .** 608

Michael Schollenberger, Thorsten Lutz, and Ewald Krämer

<b>Numerical Simulation of Laminar Separation on an Airfoil in Small-Scale Freestream Turbulence . . . . .</b>	<b>619</b>
Eike Tangermann and Markus Klein	
<b>Capability of RANS Simulations to Reproduce Flat Plate Boundary Layer Interaction with Suction and Oscillatory Blowing . . . .</b>	<b>630</b>
Junaid Ullah, Nimrod Shay, Maayan Possti, Avraham Seifert, Thorsten Lutz, and Ewald Krämer	
<b>Experimental Aerodynamics/Experimental Simulation and Test Techniques</b>	
<b>Unsteady Multi-hole Probe Measurements of the Near Wake of a Circular Cylinder at Sub-critical Reynolds Numbers . . . . .</b>	<b>643</b>
Florian M. Heckmeier, Daniel Iglesias, and Christian Breitsamter	
<b>Low Aspect Ratio Wing Under Large-Scale Turbulent Inflow Conditions at Low Reynolds Numbers . . . . .</b>	<b>653</b>
Sebastian L. Herbst, Rainer Hain, and Christian J. Kähler	
<b>Experimental and Numerical Investigation of 3-D Corner Separation in a Channel Flow with Adverse Pressure Gradient . . . . .</b>	<b>663</b>
Joachim Klinner, Michael Schroll, Christian Morsbach, Felix Möller, and Christian Willert	
<b>Visualization of Near-Wall Structures of an Isolated Cylindrical Roughness Element in a Laminar Boundary Layer Without Pressure Gradient . . . . .</b>	<b>674</b>
Jonathan Lemarechal, Esther Mäteling, Christian Klein, Dominik K. Puckert, and Ulrich Rist	
<b>Analysis of Model Mount Configurations with Regard to Force Measurements with Transient Inflow . . . . .</b>	<b>684</b>
Max Müller, Klaus Ehrenfried, James Bell, and Claus Wagner	
<b>The Reynolds-Number Effect on the Steady and Unsteady Aerodynamic Loading on Smooth and Slightly-Rough Square-Section Cylinders with Rounded Corners . . . . .</b>	<b>695</b>
Nils van Hinsberg	
<b>Investigation of 3D Coherent Structures in Turbulent Boundary Layers at High Reynolds Numbers Using MultiPulse-STB . . . . .</b>	<b>705</b>
Christina Voß, Reinhard Geisler, Matteo Novara, Markus Rütten, Florian Philipp, and Andreas Schröder	

<b>Experimental Investigation of the Influence of Permeability on Finite Wing Lift and Drag</b> . . . . .	716
Felix Wienke, Andreas Dillmann, and Markus Raffel	
<b>Aeroacoustics</b>	
<b>Influence of Flow on Noise Shielding</b> . . . . .	729
Jan Delfs, Michael Mößner, and Karl-Stéphane Rossignol	
<b>Emulation of Sound Pressure Level Spectra Based on Numerical Data</b> . . . . .	739
Benjamin Faßmann, Michaela Herr, Roland Ewert, and Jan Delfs	
<b>Progress in Helicopter Noise Prediction</b> . . . . .	749
Manuel Keßler	
<b>Design and Construction of a CROR-Model with Aeroacoustic Investigation at Different Flight Conditions</b> . . . . .	759
Christian Stanger, Manuel Keßler, and Ewald Krämer	
<b>Prediction of Trailing-Edge Noise for Separated Turbulent Boundary Layers</b> . . . . .	769
Alexandre Suryadi	
<b>Vehicle Aerodynamics</b>	
<b>Preliminary Investigations on Aerodynamic Vehicle Optimization Using the Adjoint Method with Adjoint Turbulence</b> . . . . .	783
Martin Behnsch, T. Schütz, Suad Jakirlić, and Cameron Tropea	
<b>Aerodynamic Characterisation of a Compact Car Overtaking a Heavy Vehicle</b> . . . . .	794
Henning Wilhelmi, Christoph Jessing, James Bell, Daniela Heine, Claus Wagner, and Jochen Wiedemann	
<b>Wind Energy</b>	
<b>Computational Study Using DDES with Higher Order Scheme Modeling to Predict Darrieus VAWT Noise Mechanisms</b> . . . . .	807
Amgad Dessoky, Galih Bangga, Thorsten Lutz, and Ewald Krämer	
<b>Preliminary Performance Assessment of a Twin-Rotor Horizontal Axis Wind Turbine Using Fast Aerodynamic Methods</b> . . . . .	819
Benedikt Michels	
<b>Potential Hazards of Wind Turbine Wake Vortices for Ultra-Light Sports Rotorcraft</b> . . . . .	830
Berend G. van der Wall	



**Biofluidmechanics**

<b>Aerodynamic Investigation of the Free Flapping Flight of a Saker Falcon</b> .....	843
Martin Heinold and Christian J. Kähler	
<b>Analysis of the Effects of MARME Treatment on Respiratory Flow Using the Lattice-Boltzmann Method</b> .....	853
Moritz Waldmann, Andreas Lintermann, Yoon Jeong Choi, and Wolfgang Schröder	
<b>Author Index</b> .....	865

# **Airplane Aerodynamics/Propulsion Integration**



# Implementation of a Method to Determine Aerodynamic Propeller-Wing Interaction

Nikolai Herzog<sup>(✉)</sup> and Andreas Reeh<sup>(✉)</sup>

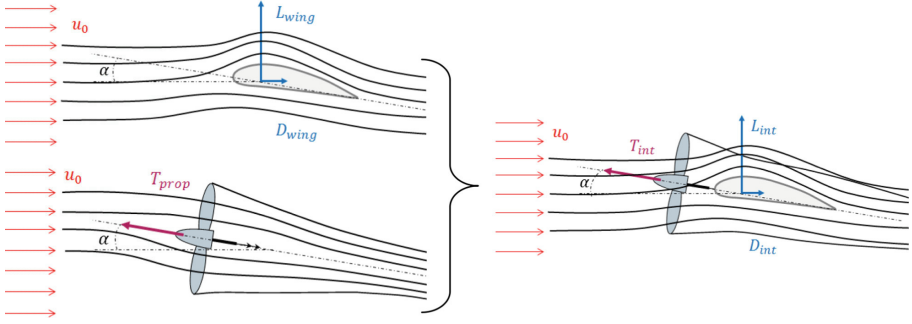
Siemens AG, Corporate Technology, Munich, Germany  
{nikolai.herzog, andreas.reeh}@siemens.com

**Abstract.** The scalability and lightweight design of electric motors within (hybrid-) electric propulsion systems facilitates the distribution of propulsion. The aerodynamic interaction of a swirling propeller slipstream and a lifting surface can be beneficial regarding a vehicle's propulsive efficiency. This report presents the implementation of a numerical method of low computational effort based on Blade Element Momentum Theory combined with a Vortex Lattice Method using a simple slipstream model. Goal of the method is to determine basic effects and trends of such aerodynamic interaction effects for conducting design studies regarding principle parameters of propeller-wing tractor configurations. The implementation is depicted and a verification is given with experimental results from literature.

**Keywords:** Propeller-Wing · Aerodynamic Interaction · Blade Element Momentum Theory · Vortex Lattice Method

## 1 Introduction

Aerodynamic effects of distributed propulsion play a key role in today's research concerning next generation aircraft designs. Especially the positioning of propellers within the flow field of a wing leads to an aerodynamic interaction. For the preliminary design this topic has been investigated recently in [1, 2] and [3]. In order to approach this interaction a simple method using Blade Element Momentum Theory (BEMT) and a Vortex Lattice Method (VLM) is implemented based on [4]. The propeller calculation uses the induced velocities of a wing's three-dimensional (3D) flow field on the propeller disc and vice versa the wing calculation considers propeller-induced velocities. It represents a preliminary design approach to model aerodynamic interaction effects regarding principle geometry parameters. Thus, by approaching the complex and unsteady flow with a stationary and rather simple approach, this method is suited for parameter studies. The aerodynamic interaction of an exemplary propeller-wing configuration has been investigated experimentally in [5, 6] and [7] using a wind-tunnel model, whose results are used here for a verification of the implemented method. Figure 1 presents qualitatively the interaction problem by showing two-dimensional (2D) streamlines of isolated and combined flow fields.



**Fig. 1.** Qualitative visualization of the aerodynamic interaction of the flow fields.

## 2 Physical Modeling

The propeller flow is modeled using BEMT extended with azimuthal discretization to consider arbitrary 3D inflow on the propeller disc using a quasi-steady sector approach. This provides the forces and moments of the propeller and the flow field input for a simple inviscid and non-deflected slipstream model. Latter is used to transfer the propeller induced velocities of each radial and azimuthal propeller disc position onto the collocation points of the VLM with a velocity development which is dependent on local slipstream contraction. Local induced velocity and Angle of Attack ( $AoA$ ) at the panels are taken into account to complement the boundary condition of no perpendicular flow. On each panel the element-wise lift and drag force components are evaluated. This procedure already provides good results for the verification case approached here and is named Single Interaction Mode (SIM) as mentioned in [4]. A Full Interaction Mode (FIM) is also implemented here, but with the use of a convergence loop for the propeller induced velocity field at the propeller disc, as shown in the flow chart of Fig. 2.

### 2.1 Blade Element Momentum Theory

The BEMT is implemented using the equations from [8] and its governing set of non-linear equations. The equations for each blade element on non-dimensional radial position  $\xi = r/R$  are extended for azimuthal angle  $\theta$  reading

$$\frac{a}{1+a} = \frac{\sigma c_y}{4F \sin^2 \phi} \quad (1)$$

$$\frac{a'}{1-a'} = \frac{\sigma c_x}{4F \cos \phi \sin \phi} \quad (2)$$

$$\phi = \arctan \frac{u_0 \cos \alpha_p \cos \beta_p (1+a)}{(u_0 (\sin \alpha_p \cos \beta_p \sin \theta + \sin \beta_p \cos \theta) + \Omega r) (1-a')} \quad (3)$$

where  $a$ ,  $a'$  and  $\phi = \beta - \alpha_i$  represent the axial interference factor, the tangential interference factor and the flow angle as a difference of the blade sectional twist

angle  $\beta$  and induced angle of attack  $\alpha_i$ . These three unknowns are determined for each non-dimensional radial position  $\xi$  and azimuthal angle  $\theta$  of the propeller disc considering the local angle of attack  $\alpha_p$  and local sideslip angle  $\beta_p$ .  $B$  represents the number of blades,  $c$  the sectional chord length,  $\sigma = \frac{Bc}{2\pi\xi R}$  the sectional solidity ratio,  $u_0$  the inflow velocity and  $\Omega$  the angular velocity of the propeller. The section force coefficients  $c_x = c_L \sin \phi + c_D \cos \phi$  and  $c_y = c_L \cos \phi - c_D \sin \phi$  are obtained using 2D airfoil polar data. The losses induced by the flow around the blade tips are modeled using the Prandtl tip loss factor  $F$ . The non-linear equations are solved iteratively for each radial and azimuthal position to determine the respective incremental values for thrust and torque and induced axial and tangential velocity components. A spatial discretization of 16 radial and 12 azimuthal elements is used. Unsteady in-plane forces and moments varying per revolution are not taken into account within this approach.

## 2.2 Slipstream Model

The flow passing through the propeller disc is assumed to contract according to a slipstream contraction factor given in [10] with the assumption of kinematic energy conservation. The contraction is here extended for azimuthal dependency and given by

$$\frac{r_s}{r} = \sqrt{\frac{1+a}{1+a\left(1+\frac{x_s}{\sqrt{r^2+x_s^2}}\right)}}, \quad (4)$$

where  $r_s/r$  denotes the radial contraction at the axial distance  $x_s$  within the slipstream. The axial and tangential velocities  $u_{s,ax}$  and  $u_{s,t}$  at this distance behind the propeller-disk read

$$u_{s,ax} = \left(\frac{r}{r_s}\right)^2 u_{p,ax} \text{ and } u_{s,t} = \frac{r}{r_s} u_{p,t}, \quad (5)$$

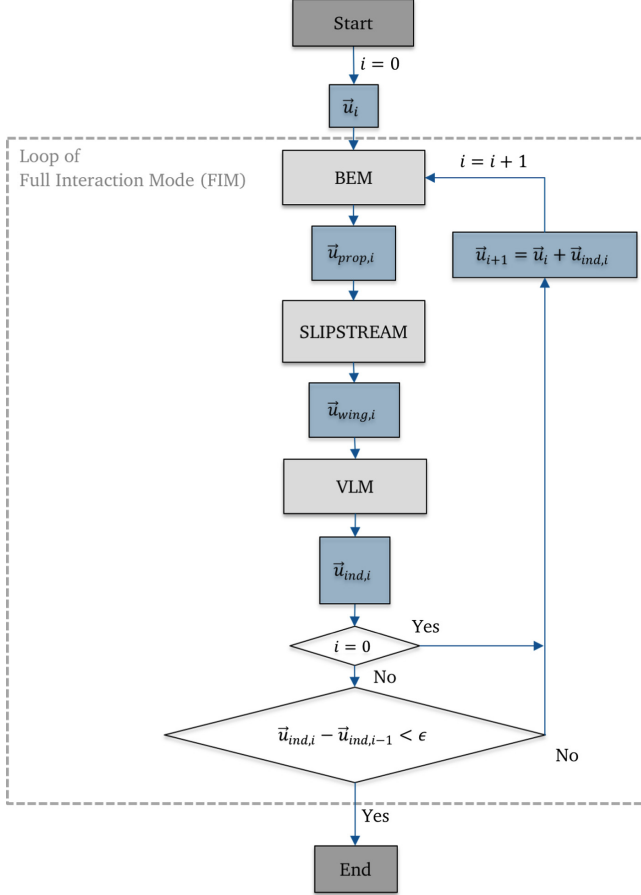
where  $u_{p,ax}$  and  $u_{p,t}$  denote the axial and tangential velocity components at the propeller disc obtained from the BEMT.

## 2.3 Vortex Lattice Method

The VLM is implemented according to [9] and the adaption for the propeller influence is implemented as described in [4]. The trailing vortices are aligned with the wing's chord direction. If a panel is located within the propeller stream-tube, the velocity vector at this collocation point considers the propeller-induced slipstream velocity reading  $\mathbf{u}_i = \mathbf{u}_0 + \mathbf{u}_{s,i}$ . The velocities induced by all horseshoe vortices onto all collocation points are formulated mathematically with the Biot-Savart law. Here the equation for discrete, straight vortex segments of finite length is applied, given by

$$\mathbf{u} = \frac{\Gamma}{4\pi} \frac{\mathbf{r}_1 \times \mathbf{r}_2}{|\mathbf{r}_1 \times \mathbf{r}_2|^2} \left[ \mathbf{r}_0 \left( \frac{\mathbf{r}_1}{r_1} - \frac{\mathbf{r}_2}{r_2} \right) \right] \quad (6)$$

where  $\Gamma$  is the circulation of the vortex segment between  $\mathbf{r}_1$  and  $\mathbf{r}_2$  and  $\mathbf{u}$  the induced velocity at  $\mathbf{r}_0$ . This law is applied for all bound and trailing vortices to set up equations for the normal components of the induced velocities of all horseshoe vortices onto all panel collocation points.



**Fig. 2.** Flow chart for the BEMT-VLM coupling within the interaction loop.

The boundary condition of zero normal flow at these points leads to the set of linear algebraic equations for the unknown circulation strengths reading  $a_{ij}\Gamma_j = -\mathbf{u}_i \cdot \mathbf{n}_i$ , where  $a_{ij}$  represents the influence coefficient of the  $j$ -th circulation strength onto the  $i$ -th panel by  $a_{ij} = \mathbf{u}_{ind,ij} \cdot \mathbf{n}_i$ . The boundary condition on the right side denoted by  $-\mathbf{u}_i \cdot \mathbf{n}_i$  is the negative value of local velocity normal to the  $i$ -th panel surface. As the circulation values at all panels are known, the lift of the  $i$ -th panel and per unit span is obtained by  $\mathbf{l}_i = \rho \mathbf{u}_i \Gamma_i$ . Here especially within the propeller slipstream the direction of the local inflow vector is

considered tilting the lift vector compared to a panel which is not located in the slipstream. In a next step, the induced angle of attack  $\alpha_{ind,i}$  and thus resulting induced drag components  $d_i$  are evaluated for all panels. The induced velocities at the collocation points  $w_{ind,i}$  are calculated with influence coefficients  $b_{ij}$ , taking exclusively the trailing vortices into account. These read  $b_{ij} = \mathbf{u}_{ind,ij}^* \cdot \mathbf{n}_i$  with  $\mathbf{u}_{ind,ij}^*$  being the induced velocity vectors only by the trailing vortices. With the original determined circulation strengths  $\Gamma_j$ , the induced velocities are obtained reading  $w_{ind,i} = b_{ij}\Gamma_j$ . A panel's induced angle of attack then reads  $\alpha_{ind,i} = \arctan(w_{ind,i}/u_i)$ . Finally the section-wise drag components by wing thickness and surface friction are obtained via XFOil and added to the induced drag components.

### 3 Results

In order to verify the implemented BEMT-VLM method the configuration described in [5] is modeled and aerodynamic force coefficients are compared to the experimental results. At first the aerodynamics of the isolated propeller and isolated wing are verified. It follows the calculation of the full propeller-wing configuration at one exemplary operating point to evaluate both induced velocity components and sectional lift and drag characteristics. Finally the configuration's force coefficients are calculated over an  $AoA$ -range with propeller-off and four different thrust settings and inflow velocity values. The model dimensions and airfoils used are given in [7].

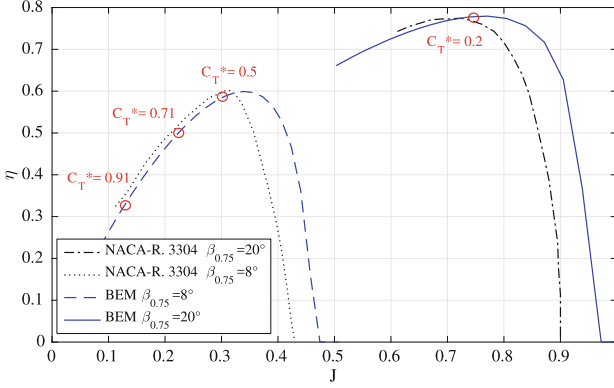
#### 3.1 Verification of BEMT and VLM

The calculated isolated propeller efficiency  $\eta = J \frac{C_T}{C_P}$  is shown in Fig. 3 over the advance ratio  $J = \frac{u}{nD}$ , where  $C_T$  is the thrust coefficient,  $C_P$  the power coefficient,  $u$  the inflow velocity,  $n$  the rotations per second and  $D$  the propeller diameter. Two different pitch settings  $\beta_{0.75R} = 8^\circ$  and  $\beta_{0.75R} = 20^\circ$  are applied. The used thrust coefficients  $C_T^*$  throughout the experimental report are based on dynamic slipstream pressure reading

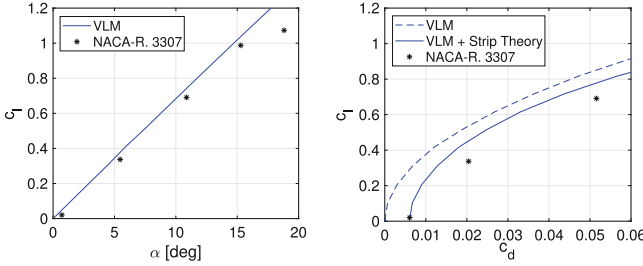
$$C_T^* = \frac{T}{q_0^* S_{prop}} \text{ with } q_0^* = \frac{\rho}{2} u^2 + \frac{T}{S_{prop}}, \quad (7)$$

where  $T$  is the propeller thrust and  $S_{prop}$  its disc area. It is used to avoid infinite force coefficients at zero wind-tunnel velocity. The main geometry parameters of the propeller blades are given in terms of twist, chord and airfoil thickness distribution. The given CLARK-Y airfoil for the propeller with a thickness of 11.7% is located only at  $0.5R$ . Since no further geometry information is available, the CLARK-Y geometry is assumed to be representative for all other radial sections within this approach. Airfoil data is generated using XFOil and sectional Reynolds number.

Furthermore propeller nacelle influence is not considered and propeller radial elements are accounted starting at  $0.2R$ . These are all possible reasons for large



**Fig. 3.** Calculated propeller efficiency compared with experimental data.



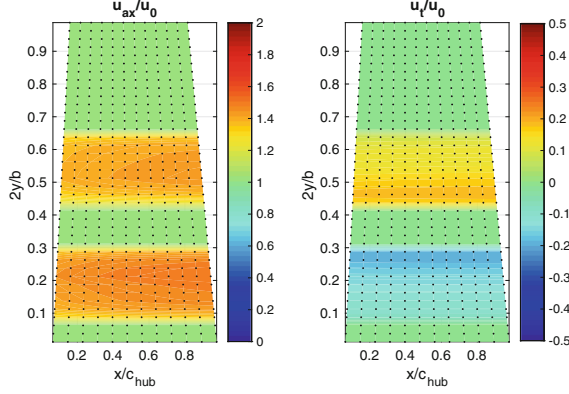
**Fig. 4.** Lift coefficient over  $AoA$  and drag polar for inviscid and viscous approach.

deviations to experimental results but are accepted here since emphasis is laid on evaluation of principle effects of the propeller-wing interaction. However the efficiency for the propeller at the points of interest is calculated with reasonable accuracy, as marked in Fig. 3. Within a next step the VLM results for the clean wing of the configuration are compared to the experimental polar in Fig. 4. NACA0015 polar data for including strip-wise the airfoil pressure and friction drag is generated also with XFOil under sectional Reynolds number. The  $\alpha$ - $c_L$ -curve shows good accuracy and the linear behavior, due to the used VLM implementation. Next to the experimental drag polar, the inviscid and viscous results are shown on the right side of Fig. 4. The calculated drag polar shows good agreement for the zero  $AoA$  case, but underestimates the experimental drag values with increasing lift coefficient.

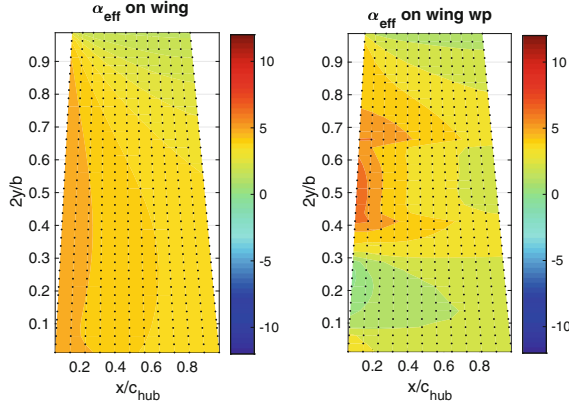
### 3.2 Verification of the Combined Method

In order to verify the correct implementation of propeller slipstream velocity components onto the VLM panels, the propeller-wing configuration is calculated at an exemplary operation point at medium thrust coefficient of  $C_T^* = 0.5$  and  $AoA = 6^\circ$ .



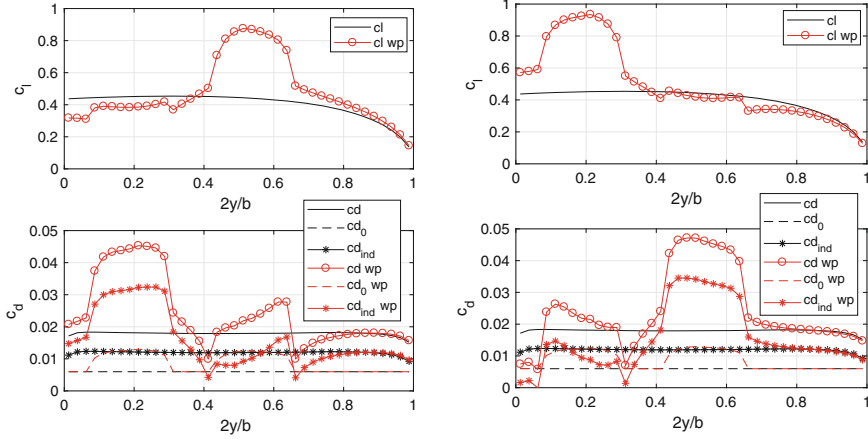


**Fig. 5.** Top-view showing non-dimensional slipstream velocity components.



**Fig. 6.** Prop-off vs. Prop-on case comparing effective  $AoA$  at the VLM panels.

The top-view of the semi-wing is shown in Fig. 5 with the propeller located left to it and rotating outboard-up direction. The non-dimensional axial and tangential velocity components obtained from the propeller calculation and resulting from the slipstream model can be seen at the respective VLM collocation points behind the propeller. The inner blade, being here the advancing blade, shows slightly larger axial velocity values than on the retreating blade side (left). Considering the sign of the tangential induced velocity (right), the outboard-up rotation of the stream-tube is verified. Moreover for this operation condition the local effective  $AoA$  at the VLM panels is shown in Fig. 6 for the propeller-off case (left) and with the influence of the propeller slipstream flow (right). Keeping this in mind Fig. 7 (left) shows the sectional values for lift and drag coefficient, compared to the isolated wing characteristics for the described condition. The coefficient values are related to free-stream velocity. Figure 7 (right) shows a



**Fig. 7.** Outboard-up (left) vs. inboard-up rotation at  $C_T^* = 0.5$  and  $AoA = 6^\circ$ .

result for everything maintained but inboard-up rotation of the propeller, as a comparison. Within the upper plots a clear increase of sectional lift coefficient can be detected behind the upward rotating blade side combined with an increase in local induced drag on the downward rotating blade side. The lower plots compare the sectional drag coefficients also including the propeller effect against the propeller-off case. Additionally the internal values for sectional parasitic and sectional induced drag contributing to the total sectional drag coefficients are shown. The effect of increased parasitic drag behind the propeller can be seen. The induced drag coefficient may be related to the local tilt of a panel's lift vector resulting from the effective  $AoA$  at each panel. The shown results are achieved with a converged interaction loop of induced propeller disc velocities (FIM) but differ negligible from the SIM results.

### 3.3 Verification of the Propeller-Wing Configuration

The considered experimental results provide vertical and horizontal force coefficients of the full configuration at different  $AoA$  over a velocity range with simultaneously reducing the propeller loading. The operating conditions for each  $AoA$ -sweep are listed in Table 1.

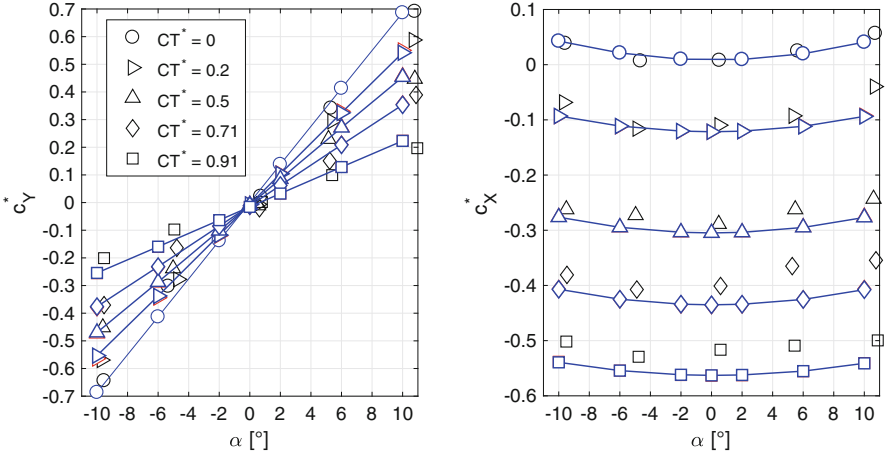
**Table 1.** Wind-tunnel velocity and isolated propeller thrust settings.

$u_0$ [m/s]	$J$ [-]	$\beta_{0.75}$ [°]	$C_T^*$ [-]	$C_T$ [-]	$DL$ [N/m <sup>2</sup> ]	RPM
25.00	-	-	-	-	-	-
22.31	0.74	20	0.20	0.0570	78.08	2936
17.65	0.30	8	0.50	0.0359	192.03	5811
13.47	0.22	8	0.71	0.0499	271.52	5887
7.49	0.13	8	0.91	0.0663	348.20	5811

In order to compare force coefficients  $c_Y^*$  and  $c_X^*$  of the tractor configuration, the propeller reaction forces also have to be included. The convention given in [5] is used reading

$$c_Y^* = \frac{L + T \sin \alpha}{q_0^* S_{wing}} \text{ and } c_X^* = \frac{D - T \cos \alpha}{q_0^* S_{wing}}, \quad (8)$$

where  $L$ ,  $D$  are the calculated lift and drag values for the blown wing,  $S_{wing}$  the projected wing surface and  $T$  the calculated propeller thrust. The different propeller thrust values are achieved by iterating the propeller RPM as it was made within the experimental campaign. For all wind-tunnel velocity and thrust value combinations thus an equal dynamic slipstream pressure of  $q_0^* = 383 \text{ N/m}^2$  is maintained. The force coefficients for the configuration are shown in Fig. 8.



**Fig. 8.** Computational force coefficients  $c_X^*$  and  $c_Y^*$  (connected symbols) are compared to experimental results (symbols only) over inflow angle.

The FIM results (blue, connected symbols) are shown and match to the SIM results (red symbols), where these are not visible. In general there are slightly different results by FIM and SIM. The lightest propeller loading result, representing a fast cruise state, shows the largest difference of a 1.6% lower  $c_Y^*$  at  $AoA = 10^\circ$  for the FIM compared to SIM. The experimental  $c_Y^*$  results (black, unconnected symbols) are met with reasonable accuracy but in general the trend is captured quite well. The horizontal force coefficients  $c_X^*$  have decreasing agreement to the experimental values with increasing thrust coefficient. The drag increase with increasing  $AoA$  is captured for all disc loading conditions. Finally the vertical and horizontal force coefficients are compared at  $6^\circ$  and  $-6^\circ$  for the described state with  $CT^* = 0.5$ . For the computational results these cases

represent outboard-up and inboard-up rotation direction, since the wing airfoil is symmetric. The quotient  $c_Y^*/c_X^*$  shows an increase of 6% for the inboard-up rotation compared to outboard-up direction, which depicts an example of a trend analysis for such a propeller-wing configuration.

## 4 Conclusion

A preliminary design tool for the aerodynamic interaction of propeller-wing tractor configurations has been implemented and computational results of a reference configuration have been presented. The approach is based on Blade Element Momentum Theory (BEMT) combined with a Vortex Lattice Method (VLM) using a simple slipstream model and enables to capture quasi-steady interaction of the flow fields. The BEMT and VLM match well with the available experimental data for the isolated components under the operation points of interest. The internal results of the combined method show its capability to capture principle interaction effects. The calculation of force coefficients of a wind-tunnel model from literature show good agreement regarding the trend of the vertical force coefficients. Although both a Single Interaction Mode and a Full Interaction Mode using a convergence loop for the induced velocity field on the propeller disc have been implemented, only the lightly loaded propeller case shows a deviation in the order of 1–2% for the vertical force component. In a next step further geometries have to be calculated and a comparison to finite-volume based methods shall be made for further verification. Although the interaction of a propeller and a wing constitutes a highly complex interaction problem, this method of low computational cost can be used in optimization loops to match propeller and wing preliminary designs. The method enables sensitivity analysis to different propeller principle designs with e.g. blade counts, tip speeds and in general the governing individual slipstream flow field.

## References

1. Ferraro, G., Kipouros, T., Savill, M., Rampurawala, A., Agostinelli, C.: Propeller-Wing Interaction Prediction for Early Design. AIAA SciTech, Maryland (2014)
2. Patterson, M.D.: Conceptual design of high-lift propeller systems for small electric aircraft, Dissertation (2016)
3. Ortun, B.: A coupled RANS/lifting-line analysis for modelling the aerodynamics of distributed propulsion. In: Conference Paper, AHS Technical Conference on Aeromechanics (2018)
4. Veldhuis, L.L.M.: Propeller wing aerodynamic interference. Delft University of Technology: Dissertation (2005)
5. Draper, J., Kuhn, R.: Investigation of the aerodynamic characteristics of a model wing-propeller combination and of the wing and propeller separately at angles of attack up to  $90^\circ$ . Technical Note 3304, NACA (1954)
6. Kuhn, R., Draper, J.: An investigation of a wing-propeller configuration employing large chord plain flaps and large diameter propellers for low speed flight and vertical take-off. Technical Note 3307, NACA (1954)

7. Kuhn, R., Draper, J.: Investigation of the aerodynamic characteristics of a model wing-propeller combination and of the wing and propeller separately at angles of attack up to  $90^\circ$ . Report 1263 NACA, Washington (1956)
8. Adkins, C., Liebeck, R.: Design of optimum propellers. *J. Propul. Power* **10**(5), 676–682 (1994)
9. Katz, J., Plotkin, A.: *Low-Speed Aerodynamics*. Mc Graw-Hill, New York (1991)
10. McCormick, B.: *Aerodynamics of V/STOL Flight*. Academic Press, New York (1967)



# Unsteady Wake and Tailplane Loads of the Common Research Model in Low Speed Stall

Andreas Waldmann<sup>1</sup>(✉), Robert Konrath<sup>2</sup>, Thorsten Lutz<sup>1</sup>,  
and Ewald Krämer<sup>1</sup>

<sup>1</sup> Universität Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany  
waldmann@iag.uni-stuttgart.de

<sup>2</sup> Deutsches Zentrum für Luft- und Raumfahrt,  
Bunsenstr. 10, 37073 Göttingen, Germany

**Abstract.** Hybrid RANS/LES simulations of the flow around the NASA Common Research Model aircraft configuration were carried out with the focus on understanding the interaction of the separated wake with the tailplane in the presence of massively separated flow on the main wing. Validation of the CFD data using PIV data obtained for the flow conditions at  $\alpha = 16^\circ$ ,  $\alpha = 18^\circ$  and  $\alpha = 20^\circ$  was carried out, confirming the generally satisfactory performance of the DDES simulations observed in earlier publications. As a next step, the wake characteristics and tailplane forces were evaluated for three angles of attack in order to investigate the flow dynamics in low speed stall. The separation characteristics were found to vary over the span. The wake size and downwash direction varied significantly with higher values of  $\alpha$ . The altered wing downwash influenced the tailplane inflow, with the load fluctuations on the latter being significantly affected by the amount of turbulent kinetic energy present in the wake.

**Keywords:** Aircraft aerodynamics · Wake flows · Post-stall flight

## 1 Introduction

Aerodynamics at the edges of the flight envelope of large civil aircraft is characterized by challenging flow conditions with high Reynolds numbers and, oftentimes, separation phenomena. The understanding of such conditions involves complex experimental or numerical investigations that are able to capture or resolve large scale unsteadiness. This motivated works such as Lutz et al. [6] and Waldmann et al. [12] in the context of the European project ESWI<sup>RP</sup>, which shed light onto the flow physics of civil aircraft at high Reynolds number stall conditions.

Low speed stall describes a condition at subsonic Mach numbers and relatively high angles of attack. The aircraft's angle of attack is significantly above  $\alpha(C_{L,max})$ , with the lift coefficient  $C_L$  typically decreasing due to large-scale flow separation. Such high angles of attack are encountered on a regular basis by