



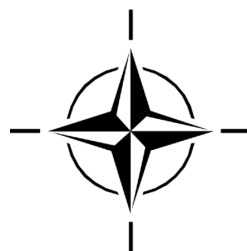
STO TECHNICAL REPORT

TR-AVT-202

# **Extensions of Fundamental Flow Physics to Practical MAV Aerodynamics**

(Elargissement de la physique fondamentale  
des écoulements à l'aérodynamique  
pratique des MAV)

AVT-202 Final Report.



Published May 2016





STO TECHNICAL REPORT

TR-AVT-202

# **Extensions of Fundamental Flow Physics to Practical MAV Aerodynamics**

(Elargissement de la physique fondamentale  
des écoulements à l'aérodynamique  
pratique des MAV)

AVT-202 Final Report.

---

# The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

The content of this publication has been reproduced directly from material supplied by STO or the authors.

Published May 2016

Copyright © STO/NATO 2016  
All Rights Reserved

ISBN 978-92-837-2030-0

Single copies of this publication or of a part of it may be made for individual use only by those organisations or individuals in NATO Nations defined by the limitation notice printed on the front cover. The approval of the STO Information Management Systems Branch is required for more than one copy to be made or an extract included in another publication. Requests to do so should be sent to the address on the back cover.

# Table of Contents

	Page
<b>List of Figures</b>	v
<b>AVT-202 Membership List</b>	x
<b>Executive Summary and Synthèse</b>	<b>ES-1</b>
<b>Chapter 1 – Introduction</b>	<b>1-1</b>
1.1 Résumé of Kinematics	1-2
1.2 Principal Scientific Questions of this Study	1-5
1.3 Brief Review of Classical Analytical Models	1-6
1.4 Reduced-Order Model of Vortex Physics	1-7
1.4.1 Non-Circulatory and Circulatory Force Contributions	1-7
1.4.2 Analytical Derivations for the Surging Plate	1-11
1.4.3 Analytical Derivations for the Pitching Plate	1-13
1.5 Parametric Variations	1-16
<b>Chapter 2 – Facilities and Methods</b>	<b>2-1</b>
2.1 AFRL	2-1
2.2 ARL	2-2
2.3 Aselsan Inc.	2-4
2.4 Cambridge University	2-4
2.5 DLR	2-6
2.6 Florida State University	2-7
2.7 Istanbul Technical University	2-8
2.8 Technical University of Braunschweig	2-9
2.9 Technical University of Delft	2-10
2.10 Wroclaw University of Technology	2-13
2.11 University of Buffalo	2-14
2.12 University of Calgary	2-15
2.13 University of Maryland	2-16
2.14 University of Michigan	2-17
<b>Chapter 3 – The Canonical Cases</b>	<b>3-1</b>
3.1 Aerodynamic Force Histories	3-1
3.2 Leading Edge and Trailing Edge Vortex Strengths and Trajectories	3-6
3.3 Evolution of Velocity and Vorticity Fields	3-10
3.3.1 Translational Pitch and Surge	3-10
3.3.2 Rotational Surge	3-14
3.3.3 Rotational Pitch	3-16

---

3.4	Application of the Low-Order Model	3-16
3.4.1	Fast Surge Case	3-16
3.4.2	Fast Pitch Case	3-19
3.4.3	Slow Pitch and Surge Cases	3-21
<b>Chapter 4 – Further Parameter Studies</b>		<b>4-1</b>
4.1	Rectilinear Pitch and Surge Nominally in Two Dimensions, and Aspect Ratio Variations in Rectilinear and Rotational Motion	4-1
4.1.1	Case 1B: Translational Surge	4-1
4.1.2	Case 1A: Translational Pitch	4-2
4.1.3	Case 2B: Rotational Surge	4-9
4.2	Variations in Reynolds Number	4-12
4.3	Variation of Reduced Frequency	4-16
4.3.1	Translational Surge	4-16
4.3.2	Translational Pitch	4-17
4.4	Variation of Pitch Pivot Point Along the Plate’s Chord	4-18
4.5	Variations in Acceleration Profiles	4-20
4.6	Variations in Translational Kinematic Modality: Plunge, Surge, and Pitch-Surge	4-21
4.6.1	Vortex Dynamics for Surge vs. Plunge	4-22
4.6.2	Lift and Drag for a Range of Kinematics	4-25
4.7	Variations in Plate Leading Edge Shape	4-27
4.8	Variations in Peak Incidence Angle	4-29
4.8.1	Translational Surge	4-30
4.8.2	Rotational Surge	4-31
<b>Chapter 5 – Conclusions</b>		<b>5-1</b>
5.1	General Observations	5-1
5.2	Résumé of Task Group’s Accomplishments, and Remaining Questions	5-2
<b>Chapter 6 – References</b>		<b>6-1</b>

## List of Figures

Figure		Page
Figure 1-1	Notional Scatter-Plot of Maximum Lift Coefficient vs. Reynolds Number for a Range of Operating Conditions, Citing in Particular the Utility of Unsteady Mechanisms for High-Lift Production at Very Low Re, where Purely Steady Means Result in Unacceptable Paucity of Lift	1-1
Figure 1-2	Schematic of the Four Prime Test Conditions	1-3
Figure 1-3	Typical Velocity Histories	1-4
Figure 1-4	Wagner's Lift Prediction and Rendition of Wagner's Bound Circulation $\Gamma$ Starting from Zero	1-6
Figure 1-5	Potential Flow Around a Flat Plate at 90° Angle of Attack	1-8
Figure 1-6	Potential Flow Streamlines Around a Stationary Counter-Rotating Vortex Pair	1-9
Figure 1-7	Schematic of Leading Edge Vortex (LEV) and Trailing Edge Vortex (TEV) with Respect to the Plate, with Coordinate System with Origin at the Plate's Leading Edge	1-10
Figure 1-8	Distance of LEV and TEV from the Plate's Leading Edge, Plotted Against Chords-Traveled by the Plate, for the Fast (Once Chord Acceleration) Translational Surging and Pitching Plates	1-12
Figure 1-9	Notional Schematic for History of Lift for the Translational Surging Plate, with Contributions During the Phase of Motion where the Plate is Surging (Non-Zero Acceleration) and where the Steady-State Relative Free-Stream Speed has been Attained	1-13
Figure 1-10	Nomenclature for 2D Pitching Plate, with Velocity Normal to the Plate, and Pivot Point Distance from the Leading Edge	1-14
Figure 1-11	Schematic from Classical Unsteady Thin Airfoil Theory, Motivating Quasi-Steady Lift Contribution Due to Pitch; Pitching Produces an Effective Angle of Attack History, or Alternative, an Effective Camber	1-15
Figure 1-12	Notional Schematic for History of Lift for the Translational Pitching Plate, with Contributions During the Phase of Motion where the Plate is Pitching (Non-Zero Pitch Acceleration is Only During the Smoothing Transients at the Start and End of the Pitching Motion) and After the Final Incidence Angle has been Attained	1-16
Figure 2-1	AFRL Water Tunnel	2-2
Figure 2-2	The ARL Oil Tank Facility	2-3
Figure 2-3	Cross-Sectional View of Unstructured Mesh for Pitching and Surging Translations	2-4
Figure 2-4	Cambridge University Department of Engineering Tow Tank	2-5
Figure 2-5	Cambridge University Tow Tank, Model Installation Scheme	2-5
Figure 2-6	DLR Tomographic-PIV Optics Set-Up in TU-Braunschweig Wind Tunnel	2-7

Figure 2-7	Typical Results of Florida State University Immersed Boundary Method Solver, Contour Levels of Vorticity for the “Fast” AR = 4 Plate Surging in Translation	2-8
Figure 2-8	ITU Experimental Set-Up	2-9
Figure 2-9	Wind Tunnel at TU-Braunschweig; Test Article and Inertial Dummy	2-10
Figure 2-10	Experimental Arrangement in the Water Tank; Dimensions of the Wing Model	2-11
Figure 2-11	Kinematics of the Revolving-Pitching and Revolving-Surging Motions	2-12
Figure 2-12	Sketch of the Top View of the Experimental Set-Up With Camera Arrangement; Wing Model and Measurement Volume Arrangement	2-13
Figure 2-13	Wing Coordinates, Laser Sheet Orientation, and Velocity Program; S-DPIV Set-Up Schematic	2-15
Figure 2-14	University of Calgary Free-Surface Water Tunnel and Hexapod Rig	2-16
Figure 2-15	University of Maryland Towing Tank: Photograph of Electric Motors Atop of Tank and Schematic of Rotating/Pitching Wing Actuation	2-16
Figure 2-16	University of Michigan, Department of Aerospace Engineering Low-Turbulence Free-Surface Water Tunnel	2-18
Figure 3-1	CL for the Fast Surging Cases	3-1
Figure 3-2	CL for the Fast Pitching Cases (LE Pivot)	3-2
Figure 3-3	CL for the Slow Surging Cases	3-2
Figure 3-4	CL for the Slow Pitching Cases (LE Pivot)	3-3
Figure 3-5	Long-Term History of CL for Fast Surging Cases	3-3
Figure 3-6	Long-Term History of CL for Fast Pitching Cases	3-4
Figure 3-7	CD for the Fast Surging Cases	3-4
Figure 3-8	CD for the Fast Pitching Cases	3-5
Figure 3-9	CD for the Slow Pitching Cases	3-5
Figure 3-10	CD for the Slow Surging Cases	3-6
Figure 3-11	Collection of Normalized LEV Circulation Histories from Various AVT-202 Contributors, for Translational Pitch and Surge Cases; Compared with Wagner’s Theoretical Curve	3-7
Figure 3-12	Normalized LEV Circulation Compared to ‘Modified’ Wagner Function for Pitch and Surge	3-8
Figure 3-13	LEV Distance from Plate Leading Edge for the Fast Translational Pitch Case	3-9
Figure 3-14	LEV and TEV Distance from Leading Edge for Fast Translational Surge and Pitch Case	3-10
Figure 3-15	Case 1a, Translational Pitch, LEV/TV Interaction Flow Visualization	3-11
Figure 3-16	Juxtaposition of Flow Visualization by Planar Laser Illumination of Fluorescent Dye in a Water Tunnel at Re = 20,000 and Black and White Rendition of Spanwise Vorticity Contours from Direct Numerical Simulation at Re = 300 for the Fast Translational Pitching Case	3-12
Figure 3-17	Frame-by-Frame Comparison of the Four Translational Cases, AR = 4 Plate, $\frac{3}{4}$ -Span Location, with PIV-Derived Vorticity and Velocity; Time-Instance as Marked in Each Row	3-14



Figure 3-18	Tableau (Phase-Averaged PIV Vorticity Contours and Projected Streamlines, University of Maryland Group) of Rotational Surge Cases	3-16
Figure 3-19	Low-Order Model Prediction for the Fast Surge Case	3-17
Figure 3-20	Variation on Figure 3-19, from the University of Maryland Group	3-18
Figure 3-21	Low-Order Model Prediction for Lift Coefficient, for the Fast Surging Case with Two Different Relative LEV-TEV Velocities (All Other Parameters are Unchanged)	3-18
Figure 3-22	Low-Order Model Prediction for the Fast Surging Case, Compared with All Available Data Sets	3-19
Figure 3-23	Low-Order Model Prediction for the Fast Pitch Case (Maryland Group)	3-20
Figure 3-24	Low-Order Model Prediction for the Fast Pitch Case (Cambridge Data)	3-20
Figure 3-25	Comparison of Low-Order Model's Prediction of Lift Coefficient History vs. that of All Available Data Sets for the Fast Pitching Case	3-21
Figure 3-26	Low-Order Model Prediction for the Slow Surging Case	3-21
Figure 3-27	Low-Order Model Prediction for the Slow Pitch Case	3-22
Figure 3-28	Low-Order Model Prediction for the Slow Pitch Case (Maryland Group)	3-23
Figure 4-1	Case 1B, Fast Translational Surge AR-Variation	4-1
Figure 4-2	Case 1B, Slow Translational Surge AR-Variation	4-2
Figure 4-3	Case 1A, Fast Translational Pitch AR-Variation	4-3
Figure 4-4	Case 1A, Slow Translational Pitch AR-Variation	4-3
Figure 4-5	Aspect Ratio Effects on 1 $c$ (Fast Case) Pitch; Lift and Drag	4-4
Figure 4-6	Aspect Ratio Effects on 6 $c$ (Slow Case) Pitch; Lift and Drag, 6 $c$ Case	4-5
Figure 4-7	Case 1A Fast Pitch, with Pitching Motion Occurring Over One Chord	4-6
Figure 4-8	Case 1A Slow Pitch, with Pitching Motion Occurring Over Six Chords	4-7
Figure 4-9	Vorticity Contours for Slow Pitch and Fast Pitch at the Following Snapshots of Time: for the Slow Case, 8.55, Corresponding to Halfway Up the Pitch Ramp, and 15.58, at the Conclusion of Pitch; for the Fast Case, Time 3.55, Corresponding to Slightly Before Halfway Up the Pitch Ramp, 5.05, at the Conclusion of Pitch, and 10.05, at a Subsequent Vortex Shedding Cycle Well After Motion is Completed	4-8
Figure 4-10	Top, or $(x, z)$ -Plane View, of an Iso-Surface of Non-Dimensional $Q = 12$ at Various $\phi$ ; AR = 2, AR = 4	4-10
Figure 4-11	Circulation vs. Phase-Angle of Rotation; Span-Averaged $\Gamma_{total}$ ; Span-Averaged $\Gamma_{LEV}$ , "Stable" LEV	4-11
Figure 4-12	$C_L$ for AR = 1 – 4, (a) vs. $t^*$ , (b) vs. $t/T_{120^\circ}$	4-11
Figure 4-13	Lift Coefficient for an AR = 4 Plate at $\theta = 45^\circ$ with Constant Acceleration from Rest, Over 1 Chord and 6 Chords, to Constant Velocity at Four Different Reynolds Numbers	4-12
Figure 4-14	AR = 4 Plate Pitching from $0^\circ$ to $45^\circ$ in 6 $c$ (Slow Case) for Reynolds Numbers 15 K through 40 K, All in Water (No Addition of Glycerin)	4-13
Figure 4-15	False-Coloring of Rhodamine-Dye Planar Laser Fluorescence (that is, Flow Visualization) of the Suction-Side Flowfield of an AR = 4 Plate Pitching from $0^\circ$ to $45^\circ$ at Various Re Values, for the "Fast" Case (Pitching Motion Occurs Over One Convective Time; Snapshot is at Completion of One Pitching Motion, by which Time the TEV has Convected $\sim 0.7 c$ Downstream of the Plate's TE)	4-14

Figure 4-16	Lift Coefficient and Drag Coefficient vs. Convective Time	4-15
Figure 4-17	Lift Coefficient for a Rotating AR = 2 Plate for a Two Orders of Magnitude Change in Reynolds Number	4-15
Figure 4-18	Lift Coefficient, Drag Coefficient, Pitching Moment Coefficient About the Mid-Chord Reference Point and Finally Lift to Drag Ratio as Functions of Chords Traveled, with Smoothed Linear Ramp of Acceleration from Rest to a Constant Velocity at Re = 20 K, Over Lengths from 0.25 $c$ to 6 $c$	4-16
Figure 4-19	Lift and Drag Coefficient Histories for AR = 4 Rectangular Flat Plate at Fast, Intermediate and Slow Pitch Rates; Pivot at Leading Edge, Re = 20 K	4-18
Figure 4-20	Pivot-Point Effects for Pure-Pitch Cases, 1 $c$ Motion, AR = 2, AR = 4 and Nominally 2D; Lift and Drag	4-19
Figure 4-21	Pivot-Point Effects for Pure-Pitch Cases, 6 $c$ Motion, AR = 4	4-19
Figure 4-22	Velocity Profiles and Lift Coefficient for an AR = 4 Plate at $\theta = 45^\circ$ Accelerating Over 6 Chords to Constant Velocity with Five Different Acceleration Profiles	4-21
Figure 4-23	Lift Coefficient Normalized by Instantaneous Dynamic Pressure for AR = 4 Plate at $\theta = 45^\circ$ Accelerating Over 6 Chords to Constant Velocity with Five Different Acceleration Profiles	4-21
Figure 4-24	Kinematics Used in this Study	4-22
Figure 4-25	Near-Mid-Plane Circulation and Convective Time Normalized with Freestream Velocity and with Effective Velocity from the Shear Layer	4-23
Figure 4-26	Vortex Positioning During Key Time Steps Between Plunge and Surge	4-24
Figure 4-27	Force Coefficients Normalized on Freestream and Effective Velocities	4-25
Figure 4-28	Comparison of Pitch Ramp, Pitch-Surge Ramp and Pure Surge-Ramp, 1 $c$ Motion, AR = 4 Flat Plate; Lift and Drag	4-26
Figure 4-29	Long-Term History of Lift and Drag for AR = 4 1 $c$ Motion Comparison	4-26
Figure 4-30	Comparison of Pitch Ramp, Pitch-Surge Ramp and Pure Surge-Ramp, 6 $c$ Motion, AR = 4 Only; Lift and Drag	4-27
Figure 4-31	Lift Coefficient Histories for the Slow Translational Pitch Case, for Plates of Sharp and Round Leading Edge, Without and With Enforcement of a Symmetry-Plane Condition	4-28
Figure 4-32	PIV Sectional Slices of Vorticity for the AR = 4 Plate: Sharp Edges and Round Edges; Slow Translational Pitch	4-28
Figure 4-33	Lift Coefficient Histories for the Slow Translational Pitch Case, for Plates of Sharp and Round Leading Edge, Without and With Enforcement of a Symmetry-Plane Condition	4-29
Figure 4-34	PIV Sectional Slices of Vorticity for the AR = 4 Plate: Sharp Edges and Round Edges; Slow Translational Pitch	4-29
Figure 4-35	Incidence-Angle Sweep (5, 10, 15, 20, 30, 45, 60, 75 and 90 degrees) for the Fast Surging Case, Re = 20,000	4-30
Figure 4-36	Iso-Surfaces of Normalized Q <sub>2</sub> -Criterion, $Q(V_i/c)^2 = 3.125$ Colored by Vorticity Magnitude; Early Time After Onset of Rotational Surge, Fast Case, Incidence Angles as Marked	4-31
Figure 4-37	2D Analog of Figure 4-36; Contours of Non-Dimensional Out-Of-Plane Vorticity ( $\omega_z c/V_i$ ) in the Reference Plane, Fast Rotational Surge Case, Incidence Angles and Chords-Traveled as Marked	4-32

---

Figure 4-38	Continuation of Figure 4-36 to Later Time (that is, Later Number of Chords-Traveled at the Reference Plane); Iso-Surfaces of $Q/(V_\infty/c)^2 = 4.68$ , Colored by Vorticity Magnitude	4-32
Figure 4-39	Continuation of Figure 4-37 to Later Time, Showing Essential Constancy of Flowfield Evolution Through Six Chords of Travel; Contours of Non-Dimensional Out-Of-Plane Vorticity ( $\omega_z c/V_\infty$ ) in the Reference Plane	4-34
Figure 4-40	Survey of Lift Coefficient and Lift-to-Drag-Ratio Histories for “Fast” Rotational Surge, with Acceleration Occurring Over One Chord at the Reference-Plane, and Fixed Incidence Angles of 15, 30, 45, 60 and 75 Degrees	4-35

# AVT-202 Membership List

## CO-CHAIRS

Dr. Michael OL  
Air Force Research Lab, AFRL/VAAA  
2130 8th Street, Building 45  
Wright-Patterson AFB, OH 45433-7542  
UNITED STATES  
Email: [michael.ol@us.af.mil](mailto:michael.ol@us.af.mil)

Prof. Holger BABINSKY  
University of Cambridge, Engineering Department  
Trumpington Street  
Cambridge CB2 1PZ  
UNITED KINGDOM  
Email: [hb@eng.cam.ac.uk](mailto:hb@eng.cam.ac.uk)

## MEMBERS

### AUSTRALIA

Mr. Jan DROBIK  
DSTO  
506 Lorimer Street  
Fishermans Bend, Victoria 3207  
Email: [jan.drobik@dsto.defence.gov.au](mailto:jan.drobik@dsto.defence.gov.au)

Dr. Jennifer L. PALMER  
DSTO, Air Vehicles Division, GPO Box 4331  
Melbourne, Victoria 3001  
Email: [jennifer.palmer@dsto.defence.gov.au](mailto:jennifer.palmer@dsto.defence.gov.au)

### CANADA

Dr. David RIVAL  
Queen's University, McLaughlin Hall  
130 Stuart Street  
Kingston, Ontario K7L 3N6  
Email: [d.e.rival@queensu.ca](mailto:d.e.rival@queensu.ca)

### FRANCE

Dr. Jean-Bernard PAQUET  
ONERA  
5 Bd. Painlevé  
59045 Lille Cedex  
Email: [jean-bernard.paquet@onera.fr](mailto:jean-bernard.paquet@onera.fr)

### GERMANY

Dr.-Ing. Rainer HAIN  
Universitaet der Bundeswehr Muenchen  
Institute of Fluid Mechanics and  
Aerodynamics  
Werner-Heisenberg-Weg 39  
D-85577 Neubiberg  
Email: [rainer.hain@unibw.de](mailto:rainer.hain@unibw.de)

Dr. Ing. Robert KONRATH  
DLR  
Institute für Aerodynamik und  
Stromungstechnik  
Experimentelle Verfahren  
Bunsenstrasse 10  
D-37073 Goettingen  
Email: [robert.konrath@dlr.de](mailto:robert.konrath@dlr.de)

Prof. Dr.-Ing. Rolf Ernst RADESPIEL  
Technische Universitaet Braunschweig  
Institut für Strömungsmechanik  
Technische Universität Braunschweig  
Hermann-Blenk-Str. 37  
D-38108 Braunschweig  
Email: [r.radespiel@tu-bs.de](mailto:r.radespiel@tu-bs.de)

### ISRAEL

Prof. Gil IOSILEVSKII  
Israel Institute of Technology  
Aerospace Engineering  
Technion City, Haifa 32000  
Email: [igil@aerodyne.technion.ac.il](mailto:igil@aerodyne.technion.ac.il)

### TURKEY

M.Sc. Mustafa PERCIN  
TU Delft  
Delft University of Technology  
Faculty of Aerospace Engineering  
Aerodynamics Group, Building 64  
Kluyverweg 2  
2629 HT Delft  
Email: [m.percin@tudelft.nl](mailto:m.percin@tudelft.nl)

**NETHERLANDS**

Dr. Ir. Bas VAN OUDHEUSDEN  
Delft University of Technology  
Dept. of Aerospace Engineering  
Kluyverweg 1  
2629 HS Delft  
Email: [b.w.vanoudheusden@tudelft.nl](mailto:b.w.vanoudheusden@tudelft.nl)

**POLAND**

PhD. Dr. Tomasz KOZLOWSKI  
Wroclaw University of Technology  
Wybrzeze Wyspianskiego 27  
50-370 Wroclaw  
Email: [tomasz.kozlowski@pwr.wroc.pl](mailto:tomasz.kozlowski@pwr.wroc.pl)

Prof. Henryk KUDELA  
Wroclaw University of Technology  
Wybrzeze Wyspianskiego 27  
50-370 Wroclaw  
Email: [henryk.kudela@pwr.wroc.pl](mailto:henryk.kudela@pwr.wroc.pl)

Prof. Krzysztof SIBILSKI  
Air Force Institute of Technology  
Ks Boleslawa 6, P.O. Box 96  
01-494 Warsaw  
Email: [sibilski@hot.pl](mailto:sibilski@hot.pl)

**TURKEY**

Dr. N.L. Oksan CETINER-YILDIRIM  
Istanbul Technical University  
Faculty of Aeronautics and Astronautics  
34469 Maslak, Istanbul  
Email: [cetiner@itu.edu.tr](mailto:cetiner@itu.edu.tr)

Mr. Arif Cem GOZUKARA  
Aselsan Inc. MGEO Division  
Cankiri yolu 7. km Akyurt  
06750 Ankara  
Email: [cgozucar@mgeo.aselsan.com.tr](mailto:cgozucar@mgeo.aselsan.com.tr)

Asst. Prof. Dr. Dilek Funda KURTULUS  
Middle East Technical University  
Aerospace Engineering Department  
06531 Ankara  
Email: [dfunda@ae.metu.edu.tr](mailto:dfunda@ae.metu.edu.tr)

Prof. Mehmet SAHIN  
Istanbul Technical University  
Faculty of Aeronautics and Astronautics  
34469 Maslak, Istanbul  
Email: [msahin@itu.edu.tr](mailto:msahin@itu.edu.tr)

**UNITED KINGDOM**

Prof. Kwing-So CHOI  
University of Nottingham  
Faculty of Engineering, University Park  
Nottingham NG7 2RD  
Email: [kwing-so.choi@nottingham.ac.uk](mailto:kwing-so.choi@nottingham.ac.uk)

**UNITED STATES**

Prof. Luis BERNAL  
University of Michigan  
1320 Beal Avenue  
Ann Arbor, MI 48109-2140  
Email: [lpb@umich.edu](mailto:lpb@umich.edu)

Dr. Kenneth GRANLUND  
Universal Technologies Corporation  
Air Force Research Lab.  
Air Vehicles Directorate  
2130 8th Street, Building 45  
Wright-Patterson AFB, OH 45433-7542  
Email: [kenneth.granlund@wpafb.af.mil](mailto:kenneth.granlund@wpafb.af.mil)

Dr. Anya JONES  
University of Maryland  
Department of Aerospace Engineering  
3154 Martin Hall  
College Park, MD 20942  
Email: [arjones@umd.edu](mailto:arjones@umd.edu)

Dr. Matthew MUNSON  
US Army Research Laboratory  
Autonomous Systems Division  
RDRL-VTA (Building 1120B)  
Aberdeen Proving Ground, MD 21005  
Email: [matthew.j.munson6.civ@mail.mil](mailto:matthew.j.munson6.civ@mail.mil)

Dr. Douglas SMITH  
Air Force Office of Scientific Research  
875 N. Randolph Street  
Suite 325, Room 3122  
Arlington, VA 22203  
Email: [douglas.smith.67@us.af.mil](mailto:douglas.smith.67@us.af.mil)

Dr. Gregg ABATE  
Air Force Office of Scientific Research (AFOSR)  
European Office of Aerospace Research and  
Development (EOARD)  
86 Blenheim Crescent  
Ruislip HA4 7HB  
UNITED KINGDOM  
Email: [gregg.abate@us.af.mil](mailto:gregg.abate@us.af.mil)

## CONTRIBUTORS

### CANADA

Prof. Dominique POIREL  
Royal Military College of Canada  
Department of Mechanical Engineering  
P.O. Box 17000, Stn Forces  
Kingston, Ontario K7K 7B4  
Email: [poirel-d@rmc.ca](mailto:poirel-d@rmc.ca)

Dr.-Ing. Weixing YUAN  
National Research Council of Canada  
Institute for Aerospace Research (Uplands, U66)  
Ottawa, Ontario K1A 0R6  
Email: [weixing.yuan@nrc-cnrc.gc.ca](mailto:weixing.yuan@nrc-cnrc.gc.ca)

### FRANCE

Mr. Olivier MARQUET  
ONERA, French Aerospace Laboratory  
Chalais Meudon Center  
Fundamental and Experimental Aerodynamic  
Department  
8, rue des Vertugadins  
92190 Meudon  
Email: [olivier.marquet@onera.fr](mailto:olivier.marquet@onera.fr)

### GERMANY

Prof. Dr. Andreas DILLMANN  
German Aerospace Center  
Institute of Aerodynamics and Flow Technology  
D-37073 Göttingen  
Email: [Andreas.Dillmann@dlr.de](mailto:Andreas.Dillmann@dlr.de)

M.Sc. Hauke EHLERS  
German Aerospace Center  
Bunsenstr. 10  
D-37073 Göttingen  
Email: [hauke.ehlers@dlr.de](mailto:hauke.ehlers@dlr.de)

Prof. Dr. Cameron TROPEA  
Technische Universität Darmstadt  
Fachgebiet Strömungslehre und Aerodynamik  
Petersenstr. 30  
D-64287 Darmstadt  
Email: [ctropea@sla.tu-darmstadt.de](mailto:ctropea@sla.tu-darmstadt.de)

Mr. Alexander WIDMANN  
TU Darmstadt  
Karolinenplatz 5  
D-64289 Darmstadt  
Email: [awidmann@sla.tu-darmstadt.de](mailto:awidmann@sla.tu-darmstadt.de)

### ISRAEL

Dr. Yossef ELIMELECH  
Technion – Israel Institute of Technology  
Haifa 32000  
Email: [meitalyossi.elimelech@gmail.com](mailto:meitalyossi.elimelech@gmail.com)

### ITALY

Dr. Flavio NOCA  
Hepia – University of Applied Sciences  
Western  
Rue de la Prairie 4  
1202 – Geneva  
SWITZERLAND  
Email: [flavio.noca@hesge.ch](mailto:flavio.noca@hesge.ch)

### TURKEY

Mr. Muhittin GOCER  
TAI – Turkish Aerospace Industries Inc.  
Fethiye Mah.Havacilik Blv.No. 17  
06980 Kazan-Ankara  
Email: [mugocer@tai.com.tr](mailto:mugocer@tai.com.tr)

### UNITED KINGDOM

Dr. Richard BOMPHREY  
University of Oxford, Department of Zoology  
South Parks Road  
Oxford OX1 3PS  
Email: [richard.bomphrey@zoo.ox.ac.uk](mailto:richard.bomphrey@zoo.ox.ac.uk)

Dr. Kevin KNOWLES  
Cranfield University  
DCMT  
Shrivenham, Wiltshire SN6 8LA  
Email: [K.Knowles@cranfield.ac.uk](mailto:K.Knowles@cranfield.ac.uk)

Dr. Nathaniel PHILLIPS  
University of Oxford  
Department of Zoology  
The Tinbergen Building  
South Parks Road  
Oxford OX1 3PS  
Email: [nathan.phillips@zoo.ox.ac.uk](mailto:nathan.phillips@zoo.ox.ac.uk)

Mr. Charles PITT FORD  
University of Cambridge  
Trumpington Street  
Cambridge CB2 1PZ  
Email: [cwp24@cam.ac.uk](mailto:cwp24@cam.ac.uk)



**UNITED KINGDOM (cont'd)**

Mr. Patrick, Robert (Robbie), James STEVENS  
University of Cambridge  
Engineering Department  
Trumpington Street  
Cambridge CB2 1PZ  
Email: [prjs2@cam.ac.uk](mailto:prjs2@cam.ac.uk)

**UNITED STATES**

Prof. Carlos CESNIK  
University of Michigan  
Department of Aerospace Engineering  
1320 Beal Avenue, 3024 FXB  
Ann Arbor, MI 48109-2140  
Email: [cesnik@umich.edu](mailto:cesnik@umich.edu)

Prof. Jeff ELDREDGE  
UCLA  
48-121A Engineering IV  
420 Westwood Plaza  
Los Angeles, CA 90095-1597  
Email: [eldredge@seas.ucla.edu](mailto:eldredge@seas.ucla.edu)

Dr. Ray GORDNIER  
Air Force Research Lab  
AFRL/VAAC  
Computational Sciences Branch  
2210 8th Street, Building 146  
Wright-Patterson AFB, OH 45433-7512  
Email: [raymond.gordnier@wpafb.af.mil](mailto:raymond.gordnier@wpafb.af.mil)

Mr. Adam HART  
University of Florida REEF  
1350 N. Poquito Road  
Shalimar, FL 32579  
Email: [darock@ufl.edu](mailto:darock@ufl.edu)

Mr. Field MANAR  
University of Maryland  
College Park, MD 20742  
Email: [fmanar@umd.edu](mailto:fmanar@umd.edu)

Mr. Peter MANCINI  
University of Maryland  
College Park, MD 20742  
Email: [petri1123@gmail.com](mailto:petri1123@gmail.com)

Mr. Ryan RANDALL  
The University of Arizona  
Aerospace and Mechanical Engineering  
P.O. Box 210119  
Tucson, AZ 85721-0119  
Email: [Ryan18rmr@yahoo.com](mailto:Ryan18rmr@yahoo.com)

Dr. Matthew RINGUETTE  
State University of New York at Buffalo  
318 Jarvis Hall  
Buffalo, NY 14260  
Email: [ringum@buffalo.edu](mailto:ringum@buffalo.edu)

Prof. Sergey SHKARAYEV  
University of Arizona  
Aerospace and Mechanical Engineering  
Department  
1130 N. Mountain Avenue  
Tucson, AZ 85721-0119  
Email: [svs@Email.arizona.edu](mailto:svs@Email.arizona.edu)

Mr. Lawrence UKEILEY  
University of Florida  
REEF Dept. of Mechanical and  
Aerospace Eng.  
1350 N. Poquito Road  
Shalimar, FL 32579  
Email: [ukeiley@reef.ufl.edu](mailto:ukeiley@reef.ufl.edu)

Dr. Miguel R. VISBAL  
Air Force Research Lab.  
Air Vehicles Directorate, AFRL/VAAC  
2210 8th Street, Building 146B  
Wright-Patterson AFB, OH 45433-7521  
Email: [miguel.visbal@wpafb.af.mil](mailto:miguel.visbal@wpafb.af.mil)

**AVT PANEL MENTOR**

Dr. Siva S. BANDA  
US Air Force Research Lab, AFRL/RQ  
2130 8th Street  
Wright-Patterson AFB, OH 45433  
UNITED STATES  
Email: [siva.banda@us.af.mil](mailto:siva.banda@us.af.mil)





<b>REPORT DOCUMENTATION PAGE</b>													
<b>1. Recipient's Reference</b>	<b>2. Originator's References</b>	<b>3. Further Reference</b>	<b>4. Security Classification of Document</b>										
	STO-TR-AVT-202 AC/323(AVT-202)TP/670	ISBN 978-92-837-2030-0	PUBLIC RELEASE										
<b>5. Originator</b>	Science and Technology Organization North Atlantic Treaty Organization BP 25, F-92201 Neuilly-sur-Seine Cedex, France												
<b>6. Title</b>	Extensions of Fundamental Flow Physics to Practical MAV Aerodynamics												
<b>7. Presented at/Sponsored by</b>	AVT-202 Final Report.												
<b>8. Author(s)/Editor(s)</b>	Multiple		<b>9. Date</b> May 2016										
<b>10. Author's/Editor's Address</b>	Multiple		<b>11. Pages</b> 124										
<b>12. Distribution Statement</b>	There are no restrictions on the distribution of this document. Information about the availability of this and other STO unclassified publications is given on the back cover.												
<b>13. Keywords/Descriptors</b>	<table style="width: 100%; border: none;"> <tr> <td style="width: 50%;">Apparent mass</td> <td style="width: 50%;">Revolving wing</td> </tr> <tr> <td>Dynamic stall</td> <td>Unsteady aerodynamics</td> </tr> <tr> <td>Flapping wing</td> <td>Unsteady aerofoil theory</td> </tr> <tr> <td>Leading edge vortex</td> <td>Vortex shedding</td> </tr> <tr> <td>Micro air vehicle</td> <td></td> </tr> </table>			Apparent mass	Revolving wing	Dynamic stall	Unsteady aerodynamics	Flapping wing	Unsteady aerofoil theory	Leading edge vortex	Vortex shedding	Micro air vehicle	
Apparent mass	Revolving wing												
Dynamic stall	Unsteady aerodynamics												
Flapping wing	Unsteady aerofoil theory												
Leading edge vortex	Vortex shedding												
Micro air vehicle													
<b>14. Abstract</b>	<p>In massively unsteady wing-flows, organized flow-separation may increase lift well above steady-state. We explore imposed rotations and rectilinear translations of rigid flat plates in incompressible flow, comparing a linear-ramp angle of attack change with streamwise acceleration (surge). In rotation, the plate revolves about an axis inboard of its inboard tip, notionally representative of a flapping-wing. Experiment, computation and analysis culminated in a two-dimensional lumped-vortex model for physics-based accounting of lift history. Rotation was found to stabilize the leading edge vortex, at least for inboard spanwise locations; the vortex sheds after saturation for the translational case. However, no advantage in peak lift or lift to drag ratio was found in rotation during the manoeuvre itself. Pitching causes a large force transient, both for rotation and translation, relative to surging; this is due to pitch-rate effects, predicted by unsteady aerofoil theory, which also accurately handles apparent-mass effects. For translation, &gt; 10 convective times are needed for the post-manoevre lift transient to relax; the rotational case reaches a steady lift value in ~ 5 convective times, and this steady value is higher than for translation. Thus rotation offers a steady-state advantage in lift, but not a transient one, owing to leading-edge vortex behaviour.</p>												





BP 25  
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE  
Télécopie 0(1)55.61.22.99 • E-mail [mailbox@cs0.nato.int](mailto:mailbox@cs0.nato.int)



**DIFFUSION DES PUBLICATIONS**  
**STO NON CLASSIFIEES**

Les publications de l'AGARD, de la RTO et de la STO peuvent parfois être obtenues auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la STO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus soit à titre personnel, soit au nom de votre organisation, sur la liste d'envoi.

Les publications de la STO, de la RTO et de l'AGARD sont également en vente auprès des agences de vente indiquées ci-dessous.

Les demandes de documents STO, RTO ou AGARD doivent comporter la dénomination « STO », « RTO » ou « AGARD » selon le cas, suivi du numéro de série. Des informations analogues, telles que le titre et la date de publication sont souhaitables.

Si vous souhaitez recevoir une notification électronique de la disponibilité des rapports de la STO au fur et à mesure de leur publication, vous pouvez consulter notre site Web (<http://www.sto.nato.int/>) et vous abonner à ce service.

### CENTRES DE DIFFUSION NATIONAUX

#### ALLEMAGNE

Streitkräfteamt / Abteilung III  
Fachinformationszentrum der Bundeswehr (FIZBw)  
Gorch-Fock-Straße 7, D-53229 Bonn

#### BELGIQUE

Royal High Institute for Defence – KHID/IRSD/RHID  
Management of Scientific & Technological Research  
for Defence, National STO Coordinator  
Royal Military Academy – Campus Renaissance  
Renaissancelaan 30, 1000 Bruxelles

#### BULGARIE

Ministry of Defence  
Defence Institute "Prof. Tsvetan Lazarov"  
"Tsvetan Lazarov" bul no.2  
1592 Sofia

#### CANADA

DGSIST  
Recherche et développement pour la défense Canada  
101 Colonel By Drive, 6 CBS  
Ottawa, Ontario K1A 0K2

#### DANEMARK

Danish Acquisition and Logistics Organization  
(DALO)  
Lautrupbjerg 1-5  
2750 Ballerup

#### ESPAGNE

Área de Cooperación Internacional en I+D  
SDGPLATIN (DGAM)  
C/ Arturo Soria 289  
28033 Madrid

#### ESTONIE

Estonian National Defence College  
Centre for Applied Research  
Riia str 12  
Tartu 51013

#### ETATS-UNIS

Defense Technical Information Center  
8725 John J. Kingman Road  
Fort Belvoir, VA 22060-6218

#### FRANCE

O.N.E.R.A. (ISP)  
29, Avenue de la Division Leclerc  
BP 72  
92322 Châtillon Cedex

#### GRECE (Correspondant)

Defence Industry & Research General  
Directorate, Research Directorate  
Fakinos Base Camp, S.T.G. 1020  
Holargos, Athens

#### HONGRIE

Hungarian Ministry of Defence  
Development and Logistics Agency  
P.O.B. 25  
H-1885 Budapest

#### ITALIE

Centro Gestione Conoscenza  
Secretariat General of Defence  
National Armaments Directorate  
Via XX Settembre 123/A  
00187 Roma

#### LUXEMBOURG

*Voir Belgique*

#### NORVEGE

Norwegian Defence Research  
Establishment  
Attn: Biblioteket  
P.O. Box 25  
NO-2007 Kjeller

#### PAYS-BAS

Royal Netherlands Military  
Academy Library  
P.O. Box 90.002  
4800 PA Breda

#### POLOGNE

Centralna Biblioteka Wojskowa  
ul. Ostrobramska 109  
04-041 Warszawa

#### PORTUGAL

Estado Maior da Força Aérea  
SDFA – Centro de Documentação  
Alfragide  
P-2720 Amadora

#### REPUBLIQUE TCHEQUE

Vojenský technický ústav s.p.  
CZ Distribution Information Centre  
Mladoboleslavská 944  
PO Box 18  
197 06 Praha 9

#### ROUMANIE

Romanian National Distribution  
Centre  
Armaments Department  
9-11, Drumul Taberei Street  
Sector 6  
061353 Bucharest

#### ROYAUME-UNI

Dstl Records Centre  
Rm G02, ISAT F, Building 5  
Dstl Porton Down  
Salisbury SP4 0JQ

#### SLOVAQUIE

Akadémia ozbrojených síl gen.  
M.R. Štefánika, Distribučné a  
informačné stredisko STO  
Demänová 393  
031 06 Liptovský Mikuláš 6

#### SLOVENIE

Ministry of Defence  
Central Registry for EU & NATO  
Vojkova 55  
1000 Ljubljana

#### TURQUIE

Milli Savunma Bakanlığı (MSB)  
ARGE ve Teknoloji Dairesi  
Başkanlığı  
06650 Bakanlıklar – Ankara

### AGENCES DE VENTE

**The British Library Document  
Supply Centre**  
Boston Spa, Wetherby  
West Yorkshire LS23 7BQ  
ROYAUME-UNI

**Canada Institute for Scientific and  
Technical Information (CISTI)**  
National Research Council Acquisitions  
Montreal Road, Building M-55  
Ottawa, Ontario K1A 0S2  
CANADA

Les demandes de documents STO, RTO ou AGARD doivent comporter la dénomination « STO », « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications STO, RTO et AGARD figurent dans le « NTIS Publications Database » (<http://www.ntis.gov>).



BP 25  
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE  
Télécopie 0(1)55.61.22.99 • E-mail [mailbox@cs.o.nato.int](mailto:mailbox@cs.o.nato.int)



**DISTRIBUTION OF UNCLASSIFIED  
STO PUBLICATIONS**

AGARD, RTO & STO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all STO reports, or just those relating to one or more specific STO Panels, they may be willing to include you (or your Organisation) in their distribution.

STO, RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for STO, RTO or AGARD documents should include the word 'STO', 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of STO reports as they are published, please visit our website (<http://www.sto.nato.int/>) from where you can register for this service.

### NATIONAL DISTRIBUTION CENTRES

#### BELGIUM

Royal High Institute for Defence – KHID/IRSD/  
RHID  
Management of Scientific & Technological  
Research for Defence, National STO Coordinator  
Royal Military Academy – Campus Renaissance  
Renaissancelaan 30  
1000 Brussels

#### BULGARIA

Ministry of Defence  
Defence Institute "Prof. Tsvetan Lazarov"  
"Tsvetan Lazarov" bul no.2  
1592 Sofia

#### CANADA

DSTKIM  
Defence Research and Development Canada  
101 Colonel By Drive, 6 CBS  
Ottawa, Ontario K1A 0K2

#### CZECH REPUBLIC

Vojenský technický ústav s.p.  
CZ Distribution Information Centre  
Mladoboleslavská 944  
PO Box 18  
197 06 Praha 9

#### DENMARK

Danish Acquisition and Logistics Organization  
(DALO)  
Lautrupbjerg 1-5  
2750 Ballerup

#### ESTONIA

Estonian National Defence College  
Centre for Applied Research  
Riaa str 12  
Tartu 51013

#### FRANCE

O.N.E.R.A. (ISP)  
29, Avenue de la Division Leclerc – BP 72  
92322 Châtillon Cedex

#### GERMANY

Streitkräfteamt / Abteilung III  
Fachinformationszentrum der  
Bundeswehr (FIZBw)  
Gorch-Fock-Straße 7  
D-53229 Bonn

#### GREECE (Point of Contact)

Defence Industry & Research General  
Directorate, Research Directorate  
Fakinos Base Camp, S.T.G. 1020  
Holargos, Athens

#### HUNGARY

Hungarian Ministry of Defence  
Development and Logistics Agency  
P.O.B. 25  
H-1885 Budapest

#### ITALY

Centro Gestione Conoscenza  
Secretariat General of Defence  
National Armaments Directorate  
Via XX Settembre 123/A  
00187 Roma

#### LUXEMBOURG

See Belgium

#### NETHERLANDS

Royal Netherlands Military  
Academy Library  
P.O. Box 90.002  
4800 PA Breda

#### NORWAY

Norwegian Defence Research  
Establishment, Attn: Biblioteket  
P.O. Box 25  
NO-2007 Kjeller

#### POLAND

Centralna Biblioteka Wojskowa  
ul. Ostrobramska 109  
04-041 Warszawa

#### PORTUGAL

Estado Maior da Força Aérea  
SDFA – Centro de Documentação  
Alfragide  
P-2720 Amadora

#### ROMANIA

Romanian National Distribution Centre  
Armaments Department  
9-11, Drumul Taberei Street  
Sector 6  
061353 Bucharest

#### SLOVAKIA

Akadémia ozbrojených síl gen  
M.R. Štefánika, Distribučné a  
informačné stredisko STO  
Demänová 393  
031 06 Liptovský Mikuláš 6

#### SLOVENIA

Ministry of Defence  
Central Registry for EU & NATO  
Vojkova 55  
1000 Ljubljana

#### SPAIN

Área de Cooperación Internacional en I+D  
SDGPLATIN (DGAM)  
C/ Arturo Soria 289  
28033 Madrid

#### TURKEY

Milli Savunma Bakanlığı (MSB)  
ARGE ve Teknoloji Dairesi Başkanlığı  
06650 Bakanlıklar – Ankara

#### UNITED KINGDOM

Dstl Records Centre  
Rm G02, ISAT F, Building 5  
Dstl Porton Down, Salisbury SP4 0JQ

#### UNITED STATES

Defense Technical Information Center  
8725 John J. Kingman Road  
Fort Belvoir, VA 22060-6218

### SALES AGENCIES

**The British Library Document  
Supply Centre**  
Boston Spa, Wetherby  
West Yorkshire LS23 7BQ  
UNITED KINGDOM

**Canada Institute for Scientific and  
Technical Information (CISTI)**  
National Research Council Acquisitions  
Montreal Road, Building M-55  
Ottawa, Ontario K1A 0S2  
CANADA

Requests for STO, RTO or AGARD documents should include the word 'STO', 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of STO, RTO and AGARD publications are given in "NTIS Publications Database" (<http://www.ntis.gov>).