



# EXPERIMENTAL STUDY ON BIO-INSPIRED WINGS WITH TUBERCLES

By

MOHAMAD AHMED ABDEL-RAHIM DESOKY

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Aerospace Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

# EXPERIMENTAL STUDY ON BIO-INSPIRED WINGS WITH TUBERCLES

By

MOHAMAD AHMED ABDEL-RAHIM DESOKY

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
**in**  
**Aerospace Engineering**

Approved by the  
Examining Committee

---

Prof. Dr. Gamal Mahmoud Sayed El-Bayoumi, Thesis Main Advisor

---

Prof. Dr. Basman Mohamad El-Hadidi, Advisor

---

Prof. Dr. Mohamad Madboli Abdel-Rahman, Internal Examiner

---

Prof. Dr. Omar Al-Farouk Abdel-Hamid, External Examiner

Professor of Aerodynamics at the Military Technical College

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

**Engineer's Name:** Mohamad Ahmad Abdel-Rahim Desoky  
**Date of Birth:** 12/08/1983  
**Nationality:** Egyptian  
**E-mail:** mohamadshorbagy@gmail.com  
**Phone:** (002) 01063479423  
**Address:** 09/119, AlAshgar Dist., 6<sup>th</sup> October City  
**Registration Date:** 01/10/ 2013  
**Awarding Date:** 2018  
**Degree:** Master of Science



**Department:** Aerospace Engineering  
**Supervisors:** Prof. Gamal Mahmoud Sayed El-Bayoumi  
Prof. Basman Mohamad El-Hadidi  
Dr. Osama Said

**Examiners:** Prof. Omar Al-Farouk Abdel-Hamid (External Examiner)  
*Professor of Aerodynamics at the Military Technical College*  
Prof. Mohamad Madboli Abdel-Rahman (Internal Examiner)  
Prof. Gamal Mahmoud Sayed El-Bayoumi (Thesis Main Advisor)  
Prof. Basman Mohamad El-Hadidi (Advisor)

**Title of Thesis:** Experimental Study on Bio-Inspired Wings with Tubercles

**Key Words:** Sinusoidal leading-edge wing; Wings with tubercles; Wavy leading-edge wings; Humpback whale flipper.

**Summary:** This work aims to answer some questions about the humpback whale flipper with its ability to delay stall and enhance post stall performance. A series of wind tunnel tests on 14 different wings with NACA 0021 profile and with different leading-edges are performed. The tests were divided into two groups: one of aspect ratio 7 which is as a convenient representative to a conventional airplane's wing, and the other group is with aspect ratio 2 as a convenient representative of a control surface aspect ratio or a MAV wing. These experiments led to the discovery of a wing leading-edge geometry constructed with peaks of the sine wave that proved to reduce the drag coefficient up to 28% and increase the lift to drag ratio up to 48% relative to its comparable sinusoidal wing. They also led to suggesting an additional design parameter that should be included in the design process to maximize the aerodynamic gains of the wings with tubercles which is the peak (or trough) width.

# EXPERIMENTAL STUDY ON BIO-INSPIRED WINGS WITH TUBERCLES

By

Mohamad Ahmed Abdel-Rahim Desoky

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Aerospace Engineering**

Under the Supervision of

**Prof. Gamal Mahmoud Sayed  
El-Bayoumi**

Professor of Aircraft Flight Mechanics &  
Control  
Aerospace Engineering Department, Faculty  
of Engineering, Cairo University

**Prof. Basman Mohamad El-  
Hadidi**

Professor of Aerodynamics  
Aerospace Engineering Department, Faculty  
of Engineering, Cairo University  
Senior Lecturer of Aerodynamics, Nanyang  
Technological University

**Dr. Osama Said**

Assistant Professor of Aircraft Flight Mechanics & Control  
Aerospace Engineering Department, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2018

## Acknowledgements

I would like to express my deepest gratitude to my supervisor professor Gamal El-Bayoumi for his great support during this work and for his encouraging words that kept me going. With the work is all done now, I realize that the best part of it was getting closer to such a great man as a professor and as a person.

I take this opportunity to express my deep appreciation to Professor Basman El-Hadidi for his close supervision, continuous follow up and fruitful discussions since the ideas contained in this work were still starting to form till the very end.

I also thank Dr. Osama Said for his encouragement during the tests and his patience driven by his experimental experience and his deep understating of the time and effort needed to get accurate and reliable results.

To my dear friend engineer Moatassem Fouda, I express my deepest gratitude for his exceptional guidance in the mechanical design and manufacturing part of this work that was not only restricted to discussions but also we shared his room/workshop assembling the parts. Without his help, this whole part would have been compromised and to him I owe a lot.

To my parents, I owe my passion for Engineering and Science in general and for everything they did to me and to my sister, I feel there is no word of gratitude can express my feelings for them.

I thank my beloved wife Nouran for her patience even through the hard times when I used to spend the whole day testing then come back showering her with engineering thoughts that she gladly listened to. For her listening, I am grateful.

I thank my beloved little daughter Farida whose smile offers me something to come home to. My candle on the road indeed.

## **Dedication**

**Dedicated with Love to the Memory of Dr. Ahmed Khaled Tawfik**

# Table of Contents

Acknowledgements .....	i
Dedication.....	ii
Table of Contents.....	iii
List of Tables.....	vi
List of Figures .....	vii
Nomenclature .....	ix
Abstract .....	xi
Chapter 1: Introduction.....	1
1.1 Humpback Whale .....	1
1.2 Applications .....	2
1.3 Thesis Objectives .....	4
1.4 Thesis Layout.....	5
Chapter 2: Literature Survey .....	6
2.1 Numerical Studies .....	6
2.2 Experimental Studies .....	7
Chapter 3: Wind Tunnel Setup .....	11
3.1 Introduction .....	11
3.2 Wind Tunnel.....	12
3.3 Wing Models .....	12
3.4 Multi-Axis Load Cell.....	12
3.4.1 Two-Axis Load Cell .....	13
3.4.2 Three-Axis Load Cell.....	13
3.4.3 Three-Axis Load Cell Upgradable to Five-Axis Load Cell .....	14
3.4.4 Five-Axis Load Cell .....	14
3.4.5 Load Cells Calibration .....	15
3.5 Pitch Control Device .....	16
3.6 Wing Installation, Experiment Alignment & Force Calculation.....	17
3.7 Data Collection .....	18
Chapter 4: Experimental Methodology .....	19
4.1 Introduction .....	19
4.2 Wind Tunnel Corrections.....	19
4.2.1 Horizontal Buoyancy .....	19
4.2.2 Solid Blockage .....	19
4.2.3 Wake Blockage.....	20
4.2.4 Streamline Curvature.....	20
4.2.5 Normal Downwash Change.....	21
4.2.6 Spanwise Downwash Distortion.....	21
4.3 Results of Wind-tunnel Corrections.....	23

4.3.1	Verification Case.....	23
4.3.2	Wings of Aspect Ratio 7 .....	24
4.3.3	Wings of Aspect Ratio 2 .....	24
4.4	<i>Analysis of the Uncertainty</i> .....	24
4.4.1	Statistical Uncertainty .....	24
4.4.2	Measurement Uncertainty.....	25
4.4.3	Uncertainty in Angle of Attack.....	25
4.4.4	Uncertainty of Load Cell.....	26
4.4.5	Uncertainty in Free-Stream Velocity .....	26
4.4.6	Combined Uncertainty .....	26
4.5	<i>Verification Case Results</i> .....	29
<b>Chapter 5: Results and Discussion .....</b>		<b>30</b>
5.1	<i>Wings under Test</i> .....	30
5.1.1	Straight7 .....	32
5.1.2	S7 .....	32
5.1.3	P7.....	32
5.1.4	S7hAhW.....	32
5.1.5	Swept7.....	32
5.1.6	E7 (1:1).....	33
5.1.7	E7 (2:1).....	33
5.1.8	SLPT7 .....	33
5.1.9	Straight2 .....	34
5.1.10	S2 .....	34
5.1.11	P2 .....	34
5.1.12	SLPT2 .....	34
5.1.13	SLT2.....	34
5.1.14	T2.....	35
5.2	<i>Aspect Ratio 7 Wings Results</i> .....	35
5.2.1	A.R 7 Wings Aerodynamic Performance.....	35
5.2.2	P7 vs S7hAhW .....	38
5.2.3	E7 (2:1) vs E7 (1:1).....	38
5.2.4	Summary of AR = 7 Wings Comparative Results.....	41
5.3	<i>Aspect Ratio 2 Wings Results</i> .....	41
5.3.1	Aerodynamic Performance, AR = 2, Re 174,000.....	41
5.3.2	S2 vs Straight2, AR=2, Re 174,000 .....	43
5.3.3	P2 vs S2, AR = 2, Re 174,000.....	44
5.3.4	T2 vs S2, AR = 2, Re = 174, 000 .....	44
5.3.5	SLPT2 vs S2, AR = 2 , Re = 174, 000 .....	44
5.3.6	SLPT2 vs S2, AR = 2, Re = 174, 000 .....	47
5.3.7	SLT2 vs S2, AR = 2, Re = 174, 000 .....	48
5.3.8	SLT2 vs SLPT2, AR = 2, Re = 174, 000.....	49
5.3.9	Aerodynamic Performance, AR = 2, Re = 120, 000 .....	50
5.3.10	Wings Aerodynamic Performance,, AR = 2 ,Re = 77, 000 .....	52
5.4	<i>Re Effect on AR = 2 Wings Comparative Performance</i> .....	53
5.5	<i>Re Effect on the Performance of Each AR = 2 Wing</i> .....	54
5.5.1	Re Effect on S2.....	54
5.5.2	Re Effect on P2 .....	55
5.5.3	Re Effect on Straight2.....	56
5.5.4	Re Effect on SLPT2.....	57
5.5.5	Re Effect on SLT2 Wing .....	58
5.5.6	Re Effect on T2 .....	59
<b>Chapter 6: Conclusions and Recommendations .....</b>		<b>61</b>
6.1	<i>Conclusions</i> .....	61



<b>6.2 Recommendations .....</b>	<b>62</b>
<b>References .....</b>	<b>63</b>
<b>Appendix A: Uncertainty Contributions .....</b>	<b>67</b>
<b>Appendix B: Wing Planforms.....</b>	<b>71</b>
<b>Appendix C: Pitch Control Device and Load Cell Mechanical Drawings .....</b>	<b>75</b>
<b>Appendix D: Experiments Tabulated Results .....</b>	<b>93</b>

## List of Tables

<b>Table 4.1:</b> Estimation of degrees of freedom for measurement uncertainties .....	27
<b>Table 4.2:</b> Values of $k_i$ , $\nu_i$ for measurement uncertainty analysis .....	27
<b>Table 4.3:</b> Nomenclature for Figure 4.2.....	28
<b>Table 5.1:</b> Nomenclature for wings under test .....	31
<b>Table 5.2:</b> Summary of $AR = 7$ Results .....	41
<b>Table 5.3:</b> Re Effect on $AR = 2$ Wings Comparative Performance .....	53
<b>Table 5.4:</b> Re Effect on $AR = 2$ Wings, for Points of Maximum Percentage difference .....	60

# List of Figures

<b>Figure 1.1:</b> A picture of Humpback Whale.....	1
<b>Figure 1.2:</b> A picture of a Scalloped wing leading edge concept .....	2
<b>Figure 1.3:</b> A picture of WhalePower .....	3
<b>Figure 1.4:</b> A picture of Dewar’s tubercled rotor blade concept .....	3
<b>Figure 1.5:</b> A picture of a spoked wheel concept .....	4
<b>Figure 2.1:</b> Hansen’s <sup>[29]</sup> hydrogen bubble visualization .....	9
<b>Figure 3.1:</b> Wind Tunnel Setup.....	11
<b>Figure 3.2:</b> Wing Model in SolidWorks® ready for 3D printing .....	12
<b>Figure 3.3:</b> Modular Two-Axis Load Cell .....	13
<b>Figure 3.4:</b> Modular Three-Axis Load Cell .....	14
<b>Figure 3.5:</b> Modular Upgradable Three-Axis Load Cell .....	14
<b>Figure 3.6:</b> Modular Five-Axis Load Cell .....	15
<b>Figure 3.7:</b> Load Cells Calibration .....	15
<b>Figure 3.8:</b> Precise Worm Gear .....	16
<b>Figure 3.9:</b> Pitch Control Device Assembly .....	16
<b>Figure 3.10:</b> Load Cell Misalignment.....	17
<b>Figure 3.11:</b> $C_D$ symmetry Check .....	18
<b>Figure 4.1:</b> Wind tunnel corrections, Verification Case .....	23
<b>Figure 4.2:</b> Relative uncertainty contributions, verification case .....	28
<b>Figure 4.3:</b> Verification results vs Hansen’s results <sup>[29]</sup> .....	29
<b>Figure 5.1:</b> Wings under test.....	30
<b>Figure 5.2:</b> Geometry of S7, P7 and S7hAhW .....	32
<b>Figure 5.3:</b> Difference between E7 (1:1), E7 (2:1) .....	33
<b>Figure 5.4:</b> Sinusoidal function near the humpback’s trailing edge tip .....	34
<b>Figure 5.5:</b> $AR = 7$ Wings Performance, $Re\ 77,000$ .....	37

<b>Figure 5.6:</b> P7 vs S7hAhW, Re 77,000.....	39
<b>Figure 5.7:</b> E7 (2:1) vs E7 (1:1), Re 77,000 .....	40
<b>Figure 5.8:</b> AR = 2 Wings Performance, Re 174,000 .....	42
<b>Figure 5.9:</b> S2 vs Straight2, Re 174,000 .....	43
<b>Figure 5.10:</b> P2 vs S2, Re 174,000 .....	45
<b>Figure 5.11:</b> T2 vs S2, Re 174,000 .....	46
<b>Figure 5.12:</b> SLPT2 vs S2, Re 174,000 .....	47
<b>Figure 5.13:</b> SLT2 vs S2, Re 174,000.....	48
<b>Figure 5.14:</b> SLPT2 vs SLT2, Re 174,000 .....	49
<b>Figure 5.15:</b> AR = 2 Wings Performance, Re 120,000 .....	51
<b>Figure 5.16:</b> AR = 2 Wings Performance, Re 77,000 .....	52
<b>Figure 5.17:</b> Re Effect on S2 Wing.....	54
<b>Figure 5.18:</b> Re Effect on P2 .....	55
<b>Figure 5.19:</b> Re Effect on Straight2 .....	56
<b>Figure 5.20:</b> Re Effect on SLPT2 .....	57
<b>Figure 5.21:</b> Re Effect on SLT2.....	58
<b>Figure 5.22:</b> Re Effect on T2 .....	59
<b>Figure A1.1:</b> Relative Uncertainty contributions, Verification Case, Re 77,000 .....	67
<b>Figure A1.2:</b> Relative Uncertainty contributions, AR2, Re 174,000.....	68
<b>Figure A1.3:</b> Relative Uncertainty contributions, Verification Case, Re 120,000 .....	69
<b>Figure A1.4:</b> Relative Uncertainty contributions for wings of A R=2, Re=77,000.....	70

# Nomenclature

$AOA$	Angle of Attack
$\alpha$	Angle of Attack
$\alpha_u$	Uncorrected Angle of Attack
$AR$	Aspect Ratio
$b$	Wing Span
$c$	Wing Chord
$C$	Test Section Area
$C_D$	Drag Coefficient
$C_{Di}$	Induced Drag Coefficient
$C_{D_o}$	Zero-lift Drag Coefficient
$C_{DU}$	Uncorrected Drag Coefficient
$c_i$	Sensitivity Coefficient
$C_L$	Lift Coefficient
$C_{L_{max}}$	Maximum Lift Coefficient
$C_{L_u}$	Uncorrected Lift Coefficient
$D$	Drag Force
$\delta$	Boundary Correction Factor
$\epsilon_{sb}$	Solid Blockage Correction Factor
$\epsilon_{wb}$	Wake Blockage Correction Factor
$F_C$	Force in Chord Direction
$F_N$	Force Normal to Chord Direction
$\Gamma$	Circulation
$K$	Coverage Factor
$K_1$	Body Shape Factor
$L$	Lift Force
$l_t$	Tail Length
$\lambda$	Wavelength
$P_w$	Peak Width
$R$	Half Width of Wind Tunnel
$Re$	Reynolds Number
$S$	Wing Surface Area
$\sigma$	Standard Deviation
$T_w$	Trough Width
$u_c$	Combined Uncertainty
$U_i$	Uncertainty of Interest
$U_\infty$	Wind tunnel airspeed

$v_{eff}$	Effective Degrees of Freedom
$v_i$	Degrees of Freedom

# Abstract

This work aims to answer some questions about the humpback whale flipper with its ability to delay stall and enhance post stall performance. A series of wind tunnel tests for 14 different wings with NACA 0021 profile and with different leading-edges are performed. The tests were divided into two groups: one of aspect ratio 7 which is as a convenient representative to a conventional airplane's wing, and the other group is with aspect ratio 2 as a convenient representative of a control surface aspect ratio or a MAV wing.

These experiments led to the discovery of a wing leading-edge geometry constructed with peaks of the sine wave that proved to reduce the drag coefficient up to 28% and increase the lift to drag ratio up to 48% relative to its comparable sinusoidal wing. They also led to suggesting an additional design parameter that should be included in the design process to maximize the aerodynamic gains of the wings with tubercles. This suggested design parameter is the peak (or trough) width. These questions also drew the attention to the tubercles found near the tip of the trailing edge of the humpback and its potential to enhance the post-stall hydrodynamic performance of the whale. They extended the idea of this configuration found in nature to a fully sinusoidal trailing edge to see if further aerodynamic enhancement can be captured.

This work also tested leading edge functions other than the sine wave approximation for the tubercles by studying elliptic and triangular functions spread along the leading edge of the wing and comparing them to a sinusoidal leading-edge wing to quantify the differences. It also studied the effect of some important aerodynamic parameters such as the sweep back angle and Reynolds number on the wings with tubercles.

**Keywords:** Sinusoidal leading-edge wing, Wings with tubercles, Wavy leading-edge wings, Humpback whale flipper.