



Ain Shams University

Faculty of Engineering

Design and Production Engineering Department

Design and Manufacturing of Inflatable Wind Turbines Blade

A Thesis Submitted in Partial Fulfillment for the Requirements of the Degree of Master of
Science in Mechanical Engineering

by

Sherif Amin Mohamed Hassan Okda

Bachelor of Science in Mechanical Engineering

Design & Production Engineering

Faculty of Engineering, Ain Shams University, June 2013

Supervised by

Prof. Dr. Adel Mohammed Monib Elsabbagh

Prof. Dr. Wael Nabil Hassan Akl

Cairo - (2019)



Ain Shams University

Faculty of Engineering

Design and Production Engineering Department

Design and Manufacturing of Inflatable Wind Turbines Blade

by

Sherif Amin Mohamed Hassan Okda

Bachelor of Science in Mechanical Engineering

(Design and Production Engineering)

Faculty of Engineering, Ain Shams University, June 2013

Examiners' Committee

Name and Affiliation	Signature
Prof. Dr. Amr Mahmoud Baz Department of Mechanical Engineering, University of Maryland
Prof. Dr. Mohamed Hazem Abdel Latif Design and Production , Ain Shams University
Prof. Dr. Adel Mohammed Monib Elsabbagh Design and Production , Ain Shams University
Prof. Dr. Wael Nabil Hassan Akl Design and Production , Ain Shams University

Date:

Statement

This thesis is submitted in partial fulfillment for the degree of Master of Science in Mechanical Engineering, to Faculty of Engineering, Ain Shams University. The author carried out the work included in this thesis at the laboratories of the Design and Production Engineering department, Faculty of Engineering, Ain Shams University. No part of this thesis has been submitted for a degree or qualification at any other university.

Sherif Amin Mohamed Hassan Okda

Signature:

Date: 14/07/2019

Researcher Data

Name: **Sherif Amin Mohamed Hassan Okda**

Date of birth: 30/7/1991

Place of birth: Alexandria

Last academic degree: Bachelor of Science

Field of specialization: Design & Production Engineering

University issued the degree: Faculty of Engineering- Ain Shams University

Date of issued degree: 2013

Current job: Demonstrator

Thesis Summary

The size of wind turbine blades is continuously growing in order to capture more energy from the wind. An innovative approach for the design and manufacturing large wind turbine blades is introduced. In this approach, blades are built of polymeric fabric which can be inflated to take the form of a HAWT (Horizontal Axis Wind Turbine) blade.

In order to withstand the wind loads, the blade is pressurized to increase its stiffness. Inflatable blades have the potential to overcome the drawbacks of traditional wind turbine blades. When compared to traditional blades made of fiberglass or carbon fibers, inflatable blades are lighter, less expensive, safer, easily manufacturable and transportable than traditional wind turbine blades.

This thesis starts by introducing inflatable structures, their applications and the motivation behind building an inflatable blade. Afterwards, a literature review is made to present the previous work done on inflatable structures that is related to the thesis topic. Related work includes: studying the bending behavior of inflatable beams, manufacturing of inflatable wings, and investigating different materials used in inflatable structures. An inflated wind turbine blade is then designed and tailored for Egyptian wind conditions. A NACA 0021 airfoil is selected for the inflatable blade. The wind turbine blade is designed using the Blade Element Momentum theory which helps to deduce the blade geometry and wind loads. After the design of the wind turbine, comes the phase of the inflatable blade fabrication. Beginning with choosing the inflatable fabric material, testing different fabric joining methods, then fabricating circular cross/section beams and testing their bending behavior. Afterwards, four prototypes of inflatable blade sections are manufactured and finally a full-size blade is fabricated.

In order to validate the inflatable blade concept, two inflatable blade sections are tested for geometrical accuracy. It is found that the average normalized error of the chord length and thickness are 3.37% and 1.67%, respectively. Afterwards the inflatable airfoil section is validated aerodynamically. They are tested in a wind tunnel in Chalmers university in Sweden, where the lift forces are measured using a six-component balance, while the drag forces are calculated from the wake measurements. The lift and drag coefficients are compared to those of a standard NACA 0021 airfoil. A good agreement between the inflatable and standard airfoils is observed. Moreover, the flow visualization is examined using both smoke generation and by using tufts. Measurements show that the boundary layer separation begins at an angle of attack not less than 15° , then it gradually increases to reach full stall at 25° . Moreover, the full-size blade is tested structurally by subjecting it to static bending loads representing the wind loads. Finally, the outcomes and conclusions of this study and future recommendations are presented.

Keywords: Inflatable blade - Inflatable airfoil - Inflatable structures - Wind tunnel testing

Acknowledgment

I would like to thank my supervisors Prof. Adel Elsabbagh and Prof. Wael Akl for offering guidance and insight throughout the course of my research. Without their knowledge and valuable time, the completion of this work would not have been possible.

Funding for this research is provided by a grant from the Science & Technology Development Fund (STDF) in Egypt. The STDF funded the fabrication of the wind blade and the visit to Chalmers University.

Also, I would like to thank ASUGARDS for funding the hot air welding machine and other experimental setups that I really helped me in my work. I would like to thank Prof. Tamer Elnady who is heading the ASUGARDS group, Abanob Fawzy for helping me with the 3D scanning, Mohemd Elgendy and Mostafa for helping me with the financial and administrative work of the research project, Mohamed Mostafa for helping me with some of the experimental setups and Ahmed Hesham for his dedicated help.

Prof. Valery Chernoray must be acknowledged for his help in the aerodynamic testing in Chalmers University. Also, I would like to thank Isaac Jonsson for helping me with the wind tunnel measurements and his informative discussions. I would also like to thank my fantastic lab mates in Chalmers University Alessandro Accorinti and Radheesh Dhanasegaran who gave me support during my stay in Sweden.

I would like to specially thank Julia Fahim for her sincere support during the whole time of my masters' studies and being a faithful friend. Thanks, must be given to Ahmed seif, Ahmed Othman, Menna Adel, Aya Adel, Basant Hany for creating a supportive environment during my work in the faculty. Special thanks to Mostafa Bedeer and Hesham who helped me in the manufacturing phase of my inflatable blade.

Finally, I would like to thank my parents, my brother and sister to whom I owe everything, they gave me support and encouragement and tolerated being busy all the time.

Table of Contents

Table of Contents III

List of Abbreviations V

List of symbols..... VI

List of Figures VII

List of Tables IX

1- Introduction 1

 1.1 What are inflatable structures? 1

 1.2 Applications of Inflatable Structures..... 1

 1.3 Motivation behind using an inflatable blade 4

 1.4 Objectives and Scope of Work..... 6

 1.4.1 Objective..... 6

 1.4.2 Scope of work..... 6

2- Literature Review 8

 2.1 Inflatable beams 8

 2.2 Manufacturing / Inflatable Wings 9

 2.3 Materials..... 14

3- Wind Turbine Blade Design 18

 3.1 Blade Element Momentum Theory 18

 3.2 Airfoil selection..... 25

 3.3 Blade design procedure 25

 3.4 BEM Results: 28

4- Inflatable Blade Fabrication 31

 4.1 Inflatable beams 31

 4.1.1 Inflatable beam manufacturing..... 31

 4.1.2 Inflatable beams bending test 32

 4.2 Results 35

 4.3 Construction of the Inflatable Blade Section 38

 4.4 Construction of a full-size blade 45

5- Experimental work & Validation 48

 5.1 Geometrical accuracy 48

5.2	Aerodynamic Testing	51
5.2.1	Lift and Drag Force Measurements	52
5.2.3	Results of aerodynamic testing	60
5.3	Flow visualization.....	66
5.4	Structural Testing of an Inflatable Blade prototype	70
6-	Conclusions and Future Work	73
6.1	Conclusions	73
6.2	Future Work	74
	References	76

List of Abbreviations

HAWT	Horizontal axis wind turbine: Wind turbine whose rotor axis is substantially parallel to the wind flow
UAVs	Unmanned Aerial Vehicles
FE	Finite Element
BEM	Blade element Momentum
NACA	National Advisory Committee for Aeronautics
PVC	Poly Vinyl Chloride
CFD	Computational Fluid Dynamics
3D	Three-Dimensional

List of symbols

a	Axial induction factor
a'	Angular induction factor
B	Number of blades
c	Chord length
c_l	Lift coefficient
c_d	Drag coefficient
c_p	Coefficient of performance
C_{lu}	Uncorrected lift coefficient
C_{du}	Uncorrected drag coefficient
F	Tip loss correction factor
h	Wind tunnel width
N	Number of blade elements
p	Pressure
P	Power
P_t	Total pressures inside wake
P_{t_0}	Total pressures outside wake
r	radius and radial direction
R	Blade tip radius
Re	Reynolds number
t	Airfoil thickness
V	Inlet flow velocity
U	Expected free wind velocity
U_{rel}	Relative wind velocity
α	Angle of attack
γ	Twist angle
ε_{sb}	Solid blockage
ε_{wb}	Wake blockage
λ	Tip speed ratio
λ_2	Body shape factor
ρ	Air density
σ	Solidity factor
ϕ	Angle of relative wind
ω	Angular velocity of the air stream.
Ω	Rotational blade speed

List of Figures

Fig. 1. Space antenna [12].	2
Fig. 2. Inflatable habitat [13].	2
Fig. 3. “The Buoyant Airborne Turbine” by Altaeros. [17].	3
Fig. 4. “The Buoyant Airborne Turbine” functioning altitude [11].	3
Fig. 5. Turbine Rotor Growth Since 1980 [13].	5
Fig. 6. The ML aviation MKL 1 tailless design plane [37].	10
Fig. 7. The Goodyear Inflatoplane [37].	10
Fig. 8. NASA Dryden's I-2000 UAV [49].	11
Fig. 9. Inflatable airfoil achieved by using pressurized tubes [10].	12
Fig. 10. Inflatable airfoil achieved by using internal spars [44].	12
Fig. 11. Inflatable airfoil achieved by tension cables [47].	13
Fig. 12. The Blade Element Model.	20
Fig. 13. A cross section showing the velocities, angles and forces acting on the blade [57].	21
Fig. 14. The iterative process of the blade design.	26
Fig. 15. Chord Distribution.	28
Fig. 16. Twist Distribution.	29
Fig. 17. Lift Forces.	30
Fig. 18. Drag Forces.	30
Fig. 19. Hot air welding machine.	32
Fig. 20. Inflatable beam test rig with beam adaptor.	33
Fig. 21. The steel rings holder.	34
Fig. 22. Inflatable beam under loading.	34
Fig. 23. The load deflection curve of 200 mm diameter beam.	35
Fig. 24. The load deflection curve of 250 mm diameter beam.	36
Fig. 25. The load deflection curve of 300 mm diameter beam.	36
Fig. 26. Beam wrinkling.	38
Fig. 27. Bumpy shape of the inflatable airfoil.	39
Fig. 28. First inflatable section prototype.	40
Fig. 29. Second inflatable section prototype.	40
Fig. 30. Failure in the Second inflatable section prototype.	41
Fig. 31. Welding of the spar to the airfoil surface. (a): first approach in which the spar material is glued to the internal surface of the airfoil. (b): The spar is glued to the outer surface.	42
Fig. 32. Third inflatable section prototype.	43
Fig. 33. A cross section view of the fourth prototype inflatable blade section.	44
Fig. 34. Exploded view of the inflatable airfoil modifications with external skin, PVC sides and wooden tail.	44
Fig. 35. Mass composition of the final prototype components.	45
Fig. 36. The optimum chord distribution (blue) vs. the linear approximation (red).	46
Fig. 37. 3D model of the proposed blade.	46

Fig. 38. The full-size inflatable blade. 47

Fig. 39. 3D laser scanning of the inflatable section. 49

Fig. 40. Geometrical error of the laser scanned inflatable airfoil (1 bar) compared to the standard NACA 0021 airfoil. 50

Fig. 41. Cross section of the Chalmers University low speed wind tunnel. 52

Fig. 42. Schematic for the installation of the inflatable blade section in the wind tunnel. .. 53

Fig. 43. A photo for the wind tunnel cross section with the inflatable blade fixed inside... 54

Fig. 44. Inflatable blade with the threaded fittings. 55

Fig. 45. Traversing system with three 5-hole pressure measuring probes. 56

Fig. 46. Measured pressure drop in the wake. 57

Fig. 47. Lift coefficient C_l and corrected C_l at different angles of attack α 60

Fig. 48. Drag coefficient C_d and corrected C_d at different angles of attack α 61

Fig. 49. Lift coefficient C_l vs. angle of attack α at three inflation pressures. 62

Fig. 50. Drag coefficient C_d vs. angle of attack α at three inflation pressures. 62

Fig. 51. Ratio C_l/C_d vs. angle of attack at three inflation pressures. 63

Fig. 52. Comparison of measured C_l of the inflated airfoil with SNL [58] and Gregorek et al. experimental data [59]. 64

Fig. 53. Comparison of measured C_d of inflated airfoil with SNL [58] numerical model and Gregorek et al. experimental data [59]. 65

Fig. 54. Smoke visualization of the inflatable blade section at different angles of attack at a wind speed of 10 m/s. 67

Fig. 55. Flow visualization of inflatable blade section in wind tunnel using tufts. 68

Fig. 57. Tufts attached to the side of the inflatable blade section at 15° angle of attack. 69

Fig. 56. Tufts attached to the side of the inflatable blade section at 25° angle of attack. 69

Fig. 58. Schematic of inflatable blade under loading. 71

Fig. 59. Full-size Inflatable blade under loading. 71

Fig. 60. Blade tip deflection at different inflation pressures. 72

List of Tables

Table 1. Properties of braided fibers materials for inflatable structure [45]..... 15

Table 2. Number of blades [57]. 27

Table 3. Twist distribution of the designed blade..... 28

Table 4. Lift and Drag forces on the blade. 29

Table 5. The stiffness and maximum load values of the three inflatable beams under different inflation pressures. 37

Table 6. Weight composition of the final prototype components..... 45

Table 7. Actual measurements captured by 3D scanning compared to the design values.... 50

1- Introduction

1.1 What are inflatable structures?

Inflatable structures, also known as tensile structures, are thin walled fabric structures that rely on the pre-tension of the fabric to gain their stiffness and carry external loads. The internal pressure applies tensile forces through the whole structure, while the external lateral loads superimpose more tensile and compressive stresses to the fabric material. The structure material cannot withstand net compressive loads as they lead to local buckling (wrinkling) in the fabric which may in turn lead to the collapse of the structure. The more the inflation pressure is, the more rigid the structure becomes. However, the fabric material has a tension limit that, if exceeded, will result in a mechanical failure.

1.2 Applications of Inflatable Structures

Inflatable structures have many advantages; they are light in weight, can be easily folded thus easily transported, easily installed or assembled, fast deployed, easily manufactured, not expensive as other structures and has a reversible behavior if subjected to a failure load as it can return to its initial position after unloading.

As a result of these advantages, inflatable structures are used in many civil, space, aeronautical and military applications. In civil applications the inflatable structures are used in air supported structures [1] such as stadium roofs, temporary buildings, and inflated tents. They can be used in aircraft escape slides and ship life rafts. Due to their light weight and ease of transportation, inflatable structures find more applications in space applications. For instance, they are used in the manufacturing of space antennas and reflectors [2-3] , as shown in Fig. 1, as well as re-entry vehicles and inflatable habitats [4-6] , as shown in Fig. 2. A review of inflatable structures applications in space is introduced by H. M. Jenkins [7].

In aeronautical applications inflatable structures are used in the manufacturing of airships, aerodynamic decelerators [8-9] and inflatable wings [10].

On the other hand, the use of inflatable structures in wind energy applications is very limited. A commercial company called Altaeros [11] introduced the Buoyant Airborne Turbine, which is shown in Fig. 3 and 4. The idea of this turbine is to install conventional small turbines at high altitudes using inflatable balloons in order to benefit from the high wind speeds. Otherwise, inflatable structures have never been used in wind energy.



Fig. 1. Space antenna [12].



Fig. 2. Inflatable habitat [13].