Airborne Wind Energy

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Green Energy and Technology

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Airborne Wind Energy

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Airborne Wind Energy

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To Corwin Hardham, 1974-2012
Pioneer of Airborne Wind Energy

Foreword

This book provides an excellent overview of the field of airborne wind energy. For someone starting to explore wind power in the upper atmosphere, the basics are now available in a single source. There are gaps in the knowledge, but those are where opportunities are.

Back in the 1970's, when I was investigating the ideas that eventually led to my paper "Crosswind Kite Power" (Journal of energy 4(3), pp. 106–111, 1980), my knowledge of the field consisted of George Pocock's book describing early 19th century kite-drawn carriages. In searching the literature I found Payne and McCutchen's 1975 patent for power generation using kites. My home computer at the time was a kit-built Sol 20 with 64 kilobytes of memory. At that time, funding for research into large-scale airborne wind energy production was non-existent.

In comparison to those days, the current state of the field is truly inspiring. Seeing the great variety of hardware that is working today is especially rewarding. I am pleased that Makani has chosen to follow the ideas for generating power by using drag power, or adding drag to the kite in the form of wind turbines, much as I discussed in my paper. With many new materials and resources, they have gone far beyond what I suggested.

When I was planning "Crosswind Kite Power", I was torn between using lift power, in which the lift of the kite pulls a load on the ground, or drag power, as the primary example for the paper. Although, at that time I was somewhat biased toward using lift power for small applications that could be more easily implemented and could be scaled to larger sizes, I decided to use an example of drag power because the lift power calculations would have required more computer power than I had available. I am delighted to see that this book provides several examples of each approach to power generation.

We are fortunate to have this compendium of information in one place. I congratulate the editors on their vision and work.

Livermore, California, June 2013 *Miles Loyd*

Preface

Dear readers,

this book is a collection of selected articles on airborne wind energy, a renewable energy technology that uses airborne devices to harness the power of the wind. Motivated by the aim to make the world less dependent on fossil energy sources, this technology is currently under investigation by researchers at start-up companies and universities. These researchers are all driven by the conviction that airborne wind energy systems have the potential to substantially contribute to the generation of cost-competitive renewable energy in the years to come, complementing other renewable energy systems.

The motivation for editing this book was that we felt a strong need for a monograph that combines and presents the many existing and exciting results from the researchers working in the field. Before this book, several authors had already written important scientific publications related to airborne wind energy, but these were scattered in diverse research journals, each with a different scope. A unified presentation of the topic was missing.

We are very happy that the present book contains reviewed articles from most of the many scientists that made important contributions to the field. In this book, they present their newest findings or make previous results more accessible to the public. We are equally happy that we succeeded in convincing nearly all start-up companies in the field to present some of their research results to the public, despite the fact that they need to protect their intellectual property. These authors present their research results in a form that allows the reader to get an understanding of the current industrial state-of-the-art of the technology, and even to draw some comparisons between the realized concepts.

One of the aims of the book is to further deepen the scientific exchange and mutual interactions within the young and vibrant airborne wind energy community. Let us in the following first give a short historical perspective on airborne wind energy, and then describe the organization of the review process and the contents of the book in more detail.

A historical perspective on airborne wind energy

The idea to use airborne devices, in particular kites, for generation of usable power dates back many centuries; most ancient civilizations knew how to fly kites, and occasionally people used them to pull loads on the ground, like carriages or ships. Probably the first dedicated research volume on the topic appears in 1827, when George Pocock publishes the book "The Aeropleustic Art or Navigation in the Air by the use of Kites, or Buoyant Sails" and experiments successfully with carriages driven by kites, which he calls *charvolant*.

However, for much over a century, most energy related innovations are related to coal and petrol; it is only during the energy crisis of the 1970s that a strong interest in non-fossil power sources arises again. This also includes airborne wind energy and, astonishingly, already in 1975 appears a patent by Payne and Mc Cutchen on the "Self-Erecting Windmill" which contains nearly all concepts of airborne wind energy for electric power generation, including on-board wind turbines and even a dual plane system. Four years later, in 1979, the Australian engineer Bryan Roberts performs first experiments towards the exploitation of high altitude wind power by devices that he calls the *flying electric generators*.

A seminal contribution to the field appears in 1980, when the American engineer Miles Loyd publishes his article "Crosswind Kite Power" and with it lays the foundation for a quantitative analysis of airborne wind power systems. Loyd also patents a crosswind system that uses on-board wind turbines which transmit their power via three moving tethers to the ground. In the two decades from 1980 to 2000, airborne wind energy remains nearly stagnant, while the ground-based, conventional wind power technology develops tremendously and establishes a de-facto standard with the three-bladed Danish wind turbine.

However, with the advent of new tether and control technologies, airborne wind energy research starts to accelerate again at the turn of the century, as illustrated in Fig. 1. In 1997, the Dutch astronaut and university professor Wubbo Ockels patents

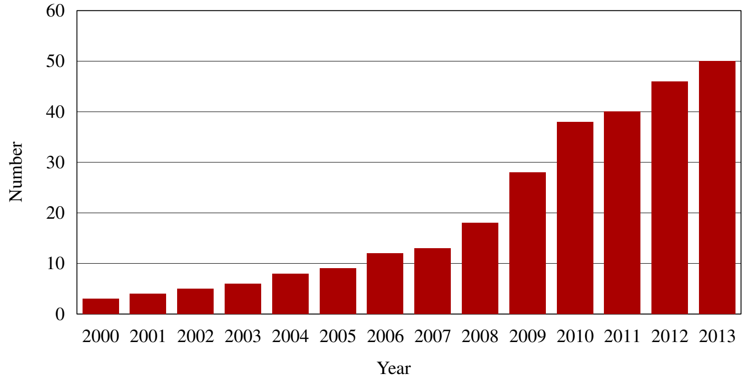

Fig. 1 Number of institutions actively involved in airborne wind energy (data 2000-2011 contributed by Allister Furey)

the concept of the Laddermill, a series of multiple stacked kites driving a generator on the ground, and starts to investigate flexible wing systems in pumping mode with his team at Delft University of Technology. In 2001, the company SkySails is founded in Germany, and develops the first commercial kite system for ship traction. A large-scale variant is experimentally demonstrated and flown automatically a few years later on cargo ships.

In 2005, a high altitude wind power (HAWP) conference was held at AeroVironment in California, while in 2006, the company Makani Power is founded in California, with substantial funds by google. Initially working on flexible pumping kite concepts, the focus is later shifted to rigid wings with on-board generation. Simultaneously, the companies WindLift in the US and NTS in Germany are founded, and the KiteGen project in Italy realizes a pumping kite power system based on a dual line surf kite. In 2007, an international workshop on “modelling and optimization of power generating kites” is held at KU Leuven, Belgium, and a variety of research papers on the control of airborne wind energy systems appear.

In 2008, the start-up company Joby Energy is founded in California, and helps to create the Airborne Wind Energy Consortium (AWEC). The idea to form the AWEC emerges in 2009, when a high-altitude wind power conference is held in Chico, California. In 2010, the first Airborne Wind Energy Conference (AWEC 2010) is held in Stanford. From then on, there is one annual international conference, alternating

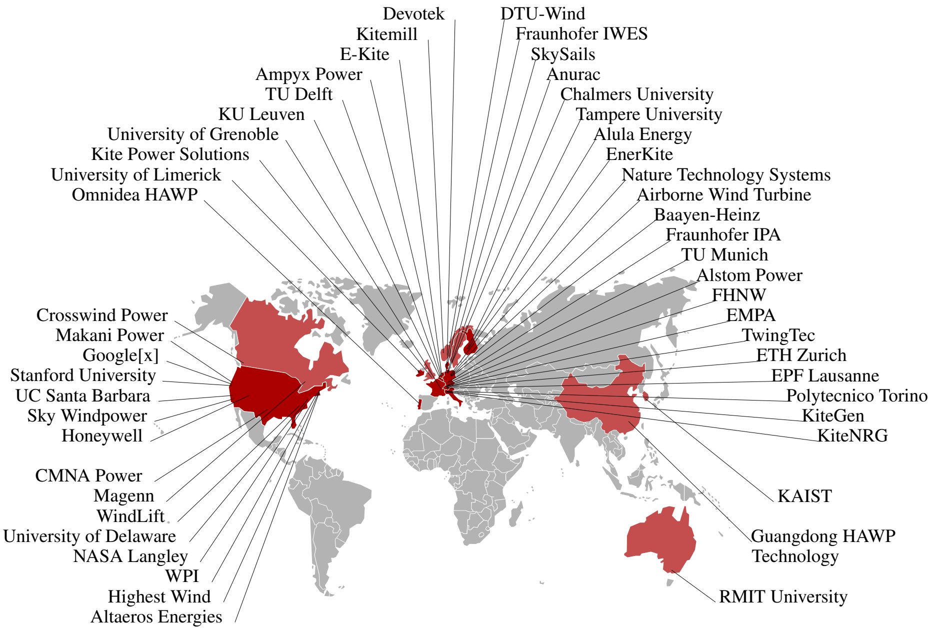

Fig. 2 Airborne wind energy research and development activities by country and by team. Countries with academic or commercial activities in 2013 are colored in red, while dark red indicates that one or more authors from this country contributed to this book.

between the US and Europe. The second conference in this series takes place 2011 in Leuven (AWEC 2011) and the companies Makani Power and SkySails demonstrate fully automatic flight including start and landing.

In 2012, the third conference takes place in Virginia (AWEC 2012). In the same year, Corwin Hardham, CEO of Makani, dies unexpectedly, to the regret of the whole AWE community. In spring 2013, Makani Power is acquired by Google[X], the secretive division of Google dedicated to futuristic long-shot projects, and in autumn 2013 the fourth conference is held in Berlin (AWEC 2013). Also in 2013, the first monograph on "Airborne Wind Energy" is published by Springer Verlag in form of the present book.

Fig. 2 maps the worldwide commercial and academic research and development activities on Airborne Wind Energy in 2013, and also shows the many teams that have contributed to this volume.

About this book

The present book consists of 35 independently written chapters and is the work of many people. Each of the submitted articles underwent a rigorous review process with at least two and up to four reviews per submitted article, and with two consecutive review rounds for the majority of the articles. Altogether, 44 articles were submitted, and 62 reviewers helped to ensure and improve their quality. The names of the reviewers are listed in the following section and we express our thanks for their fast, competent and constructive reviews. To keep the review process as anonymous and impartial as possible, the three editors distributed the submitted articles among each other, each organizing the review process for one subset of articles independently. We did not disclose the names of each article's reviewers to each other, and articles in which one of the editors was directly or indirectly involved were handled by another editor.

We have ordered the chapters into five parts. Part I on "Fundamentals" contains seven general articles explaining the principles of airborne wind energy and its different variants, of meteorology, the history of kites, and financing strategies. Part II on "System Modeling, Optimization and Control" contains eight articles that develop and use detailed dynamic models for simulation, optimization, and control of airborne wind energy systems, while Part III on "Analysis of Flexible Kite Dynamics" collects four articles that focus on the particularly challenging simulation problems related to flexible kites. Part IV "Implemented Concepts" contains eleven articles each of which presents developed prototypes together with real-world experimental results obtained with the different concepts. Finally, in Part V on "Component Design", five articles are collected that address in detail the technical challenges for some of the components of airborne wind energy.

We hope that the present book will serve as a reference to academic and industrial practitioners of airborne wind energy and will allow the interested public to assess the current state-of-the-art of the different implemented concepts. Most important, we do hope that reading the book will be as entertaining and interesting for the general reader as it was for us in the role of editors.

Berlin, *Uwe Ahrens*
Leuven, *Moritz Diehl*
Delft, *Roland Schmehl*
June 2013

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Contents

Nomenclature

a	acceleration [m/s^2]
A	surface area [m^2]
AR	aspect ratio
c_a	availability factor
c_f	capacity factor
B	magnetic field [mGauss]
C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
C_M	aerodynamic moment coefficient
CF	crest factor
d	diameter [m]
D	duty cycle
D or F_D	aerodynamic drag force [N]
E	energy [J]
E	elastic modulus [N/m^2]
f	frequency [1/s]
f	reeling factor
$\mathbf{F}_a$	resultant aerodynamic force [N]
F_D or D	aerodynamic drag force [N]
F_L or L	aerodynamic lift force [N]
$\mathbf{g}$	gravitational acceleration [m/s^2]
h	altitude above ground [m]
I	electrical current [A]
I	moment of inertia [kg m^2]
L	power losses [W]
L or F_L	aerodynamic lift force [N]
l	length [m]
$\mathbf{M}_a$	aerodynamic moment [Nm]
m	mass [kg]
$\mathbf{n}$	normal vector
p	static pressure [N/m^2]

P	power [W]
r	radius [m]
$\mathbf{r}$	position [m]
S	surface area [m^2]
S	safety factor
t	time [s]
T	temperature [K]
T or F_t	tether force [N]
$\mathbf{u}$	control vector
U	electrical voltage [V]
$\mathbf{u}$	control vector
v	velocity [m/s]
v_a	apparent wind velocity [m/s]
v_w	wind velocity [m/s]
v_∞	freestream or upstream velocity [m/s]
$\mathbf{x}$	state vector
α	angle of attack [rad]
β	elevation angle [rad]
γ	flight path angle [rad]
ζ	power factor
η	efficiency
κ	camber
λ	crosswind factor
μ	coefficient of viscous friction [Nms]
μ	dynamic viscosity [Ns/m^2]
ν	kinematic viscosity [m^2/s]
ρ	air density [kg/m^3]
τ	torque [Nm]
τ_μ	friction torque [Nm]
ω	angular velocity [rad/s]

Subscripts

a	apparent
c	cycle
e	electrical
f	force
g	ground
i	reel-in
k	kite
m	mechanical
p	pumping
o	reel-out

r	radial
t	tether
v	velocity
w	wind
τ	tangential

Coordinates and rotation sets

P, Q, R	roll, pitch, yaw angular velocities [1/s]
r, θ, ϕ	radial distance, polar/elevation angle, and azimuthal angle [rad]
x, y, z	Cartesian coordinates [m]
ϕ, θ, ψ	roll, pitch, yaw angles [rad]