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Morphing Aerospace Vehicles and Structures

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MORPHING AEROSPACE VEHICLES AND STRUCTURES

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MORPHING AEROSPACE VEHICLES AND STRUCTURES

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WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2012
© 2012, John Wiley & Sons, Ltd

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Morphing aerospace vehicles and structures / edited by John Valasek.
p. cm. – (AIAA progress series)
Includes bibliographical references and index.
ISBN 978-0-470-97286-1 (cloth) – ISBN 978-1-60086-903-7
1. Aerospace engineering. 2. Wing-warping (Aerodynamics) 3. Airplanes–Design and construction. 4. Airplanes–Wings–Design and construction. I. Valasek, John. II. American Institute of Aeronautics and Astronautics.
TL565.M67 2012
629.1′2–dc23
2011045495

A catalogue record for this book is available from the British Library.

ISBN: 978-0-470-97286-1

Typeset in 10/12pt Times by Aptara Inc., New Delhi, India

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Foreword

Morphing systems are reconfigurable systems whose features include geometric shape change, but also can include color, aural or electromagnetic changes. Morphing aircraft with retractable landing gear, flaps and slats and variable sweep wings are not unusual today, but they were futuristic 70 or 80 years ago. Who has not marveled to see the morphing wing of a commercial jet robotically change shape as it deploys spoilers and flaps when landing? On the other hand, the missions for these aircraft are conventional. This book looks at morphing systems with an eye to the future in which missions will be challenging and today's solutions simply will not work.

I first came across the term "morphology" in 1971 while reading the final draft of Professor Holt Ashley's textbook *Engineering Analysis of Flight Vehicles*. His first chapter is entitled "Morphology of the Airplane." Holt was my research adviser at Stanford in the late 1960s and, more importantly a distinguished educator, researcher, engineer and master of the written English language. When I suggested that he change "morphology" to something like "shape," he replied: "But morphology is such a wonderful word! So descriptive!" And so it is.

My four-year stint as a DARPA program manager included development of game-changing morphing aircraft for a specific military mission. The DARPA program was very successful and we showed that: (1) morphing shape change is not expensive, compared to the system benefits it provides; and (2) morphing concepts succeed when the airplane mission involves design conflicts requiring the choice of either building a large wing/engine combination or a smaller mechanized wing with smaller engines and fuel requirements. Sometimes, no other approach other than morphing worked.

Future aircraft missions will require aircraft shape and feature changes that, in turn, require new component technologies, from engines to wing mechanisms to smart materials, as well as expanded analysis techniques. This book provides valuable information to begin this journey into the future. It begins with bio-inspiration. The Russian engineer Genrich Altshuller observed that "In nature there are lots of hidden patents." Chapter 8 on perching aircraft suggests a unique use for integrated morphing technologies, while Chapter 9 on smart materials and control of morphing devices provides a window on the challenging problems of system integration.

Oliver Wendell Holmes once wrote: “A man’s mind stretched by a new idea can never go back to its original dimensions.” This book provides an opportunity for mind expansion. I encourage you to read it, absorb the ideas and contribute to the morphing aircraft future.

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Series Preface

The field of aerospace is wide ranging and multi-disciplinary, covering a large variety of products, disciplines and domains, not merely in engineering but in many related supporting activities. These combine to enable the aerospace industry to produce exciting and technologically advanced vehicles. The wealth of knowledge and experience that has been gained by expert practitioners in the various aerospace fields needs to be passed onto others working in the industry, including those just entering from University.

The *Aerospace Series* aims to be a practical and topical series of books aimed at engineering professionals, operators, users and allied professions such as commercial and legal executives in the aerospace industry. The range of topics is intended to be wide ranging, covering design and development, manufacture, operation and support of aircraft as well as topics such as infrastructure operations and developments in research and technology. The intention is to provide a source of relevant information that will be of interest and benefit to all those people working in aerospace.

There has been much interest world-wide in the development of morphing air-vehicles to improve performance, and possibly change mission requirements in-flight, by enabling the air-vehicle to adjust its external shape and structural/aerodynamic/control characteristics to adapt to the changing flight environment. Many different concepts have been proposed, with a few being demonstrated on a range of different prototype flying vehicles.

This book, *Morphing Aerospace Vehicles and Structures*, is the first textbook to provide an overview of the current status of morphing air-vehicles, and to provide guidance as to likely future directions in this exciting technology. Starting with the bio-inspired geometric changes of insects, birds and bats that are the motivation for many morphing concepts, the book then describes issues relating to the flight control and dynamics of morphing air-vehicles, and also the application of smart materials and hierarchical control for morphing. It is a welcome addition to the Wiley Aerospace Series.

Peter Belobaba, Jonathan Cooper, Roy Langton and Allan Seabridge

Acknowledgments

Several individuals and organizations have made special and significant contributions to this book, and I wish to recognize their efforts. My wife Stephanie has encouraged me to write a book for many years. This book would not have been realized without her tireless support and steadfast encouragement, all while she pursued her graduate studies. My graduate and undergraduate research students who contributed to this book have been a joy to work with, and a constant source of inspiration. Teachers can learn from their students, and indeed I have and continue to do so. I am grateful to many of my faculty colleagues in various departments at Texas A&M University who have shared their valuable insights and provided suggestions on the research. Special thanks are bestowed upon Dr. Sharon M. Swartz of Brown University, for graciously providing a specialized review and critique of Chapter 2.

This book was begun during my Faculty Development Leave, and I am indebted to my Department Heads in the Aerospace Engineering Department at Texas A&M University during and since that time: Dr. Helen L. Reed, Dr. Walter E. Haisler, and Dr. Dimitris C. Lagoudas. They not only encouraged me to pursue it, but also provided me with the full opportunity and means to do so.

While all of the authors in this book have obtained funding for their portion of the work from various sponsors, two sponsors in particular have provided exceptional support overall. The U.S. Air Force Office of Scientific Research provided support under contract FA9550-08-1-0038, with technical monitors Dr. Scott Wells, Dr. William M. McEneaney, and Dr. Fariba Fahroo. The National Aeronautics and Space Administration was instrumental in providing early support through the Texas Institute of Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles (TiiMS). The technical monitor was Dr. Tom Gates. This generous support is gratefully acknowledged.

The wonderful staff at John Wiley & Sons Ltd., Chichester, have been instrumental and contributed a great deal to this endeavor. They have also been only a pleasure to work with. Commissioning Editors David Palmer and Debbie Cox conceived the original idea for the book, approached me with it and patiently encouraged me to pursue it, and then championed it to the publisher. Project Editors Claire Bailey and Liz Wingett skillfully managed both the author and the manuscript to completion. Project Editor of Engineering Technology Nicky Skinner was a warm and generous colleague whom I enjoyed getting to know and work with, who tragically passed on during the final stages. She is greatly missed by me and all who knew her, and her memory is embossed in the final product.

Finally, I would like to thank all of the authors who contributed chapters and their expertise. I am blessed to have you as colleagues and collaborators, and pleased to call you friends.

John Valasek
College Station, Texas, USA
July 2011

1

Introduction

John Valasek
Texas A&M University, USA

> *A flying machine is impossible, in spite of the testimony of the birds*
> —John Le Conte, well-known naturalist, ”The Problem of the Flying Machine,” Popular Science Monthly, November 1888, p. 69.

1.1 Introduction

Current interest in morphing vehicles has been fueled by advances in smart technologies such as materials, sensors, actuators, their associated support hardware and microelectronics. These advances have led to a series of breakthroughs in a wide variety of disciplines that, when fully realized for aircraft applications, have the potential to produce large improvements in aircraft safety, affordability, and environmental compatibility. The road to these advances and applications is paved with the efforts of pioneers going back several centuries. This chapter seeks to succinctly map out this road by highlighting the contributions of these pioneers and showing the historical connections between bio-inspiration and aeronautical engineering. A second objective is to demonstrate that the field of morphing has now come nearly full circle over the past 100 plus years. Birds inspired the pioneer aviators, who sought solutions to aerodynamic and control problems of flight. But a smooth and continuous shape-changing capability like that of birds was beyond the technologies of the day, so the concept of variable geometry using conventional hinges and pivots evolved and was used for many years. With new results in bio-inspiration and recent advances in aerodynamics, controls, structures, and materials, researchers are finally converging upon the set of tools and technologies needed to realize the original dream of aircraft which are capable of smooth and continuous shape-changing. The focus and scope of this chapter are intentionally limited to concepts and aircraft that are accessible through the unclassified, open literature.

Morphing Aerospace Vehicles and Structures, First Edition. Edited by John Valasek.

Figure 1.1 Lilienthal Glider circa 1880s showing bird influence. Reproduced by permission of Archives Otto-Lilienthal Museum

1.2 The Early Years: Bio-Inspiration

Otto Lilienthal was a nineteenth-century Prussian aviator who had a lifelong fascination with bird flight which led him into a professional career as a designer. He appeared on the aviation scene in 1891 by designing, building, and flying a series of gliders. Between 1891 and 1896 he completed nearly 2,000 flights in 16 different types of gliders, an example of which is shown in Figure 1.1. The wings of these gliders were described as resembling "the outstretched pinions of a soaring bird." The bird species which captivated him most were storks, and the extent to which birds influenced Lilienthal is evidenced by two of the many books which he wrote on aviation: *Our Teachers in Soaring Flight* in 1897, and *Birdflight as the Basis for Aviation: A Contribution toward a System of Aviation* in 1889 (Lilienthal 1889). His observations on bird twist and camber distributions were influential in the development of his air-pressure tables and airfoil data. Interestingly, Lilienthal also made attempts at powered flight but chose to only study wings with orntithopteric wingtips. His insistence on the use of flapping wing tips in preference to a conventional propeller is an indication of the extent to which he was captivated by bird flight (Crouch 1989). Several early pioneers recognized the value in morphing as a control effect. Edson Fessenden Gallaudet, Professor of Physics at Yale, applied the concept of wing warping to a kite in 1898. While not entirely successful, this kite nonetheless embodied the basic structural concepts which would appear in aircraft designs much later (Crouch 1989). Independently, Orville and Wilbur Wright, correctly deduced that wing warping could provide lateral control. Wilbur remarked to Octave Chanute in 1900 that "My observation of the flight of buzzards leads me to believe that they regain their lateral balance, when partly overturned by a gust of wind, by a torsion of the tips of the wings. If the rear edge of the right wing tip is twisted upward and the left downward, the bird becomes an animated windmill and instantly begins to turn, a line from its head to its tail being the axis" (Wright 1900). This observation led to the design of the 1902 Wright Glider, which incorporated wing warping for lateral (roll) control (Figure 1.2). The warping was accomplished by wires attached to the pilot's belt, which were controlled by his shifting body position. Although this craft was flown by the Wrights as both a kite and a glider, it was during flights of the latter type that the need for a directional (yaw) control was first realized, and then solved with the creation of the rudder.

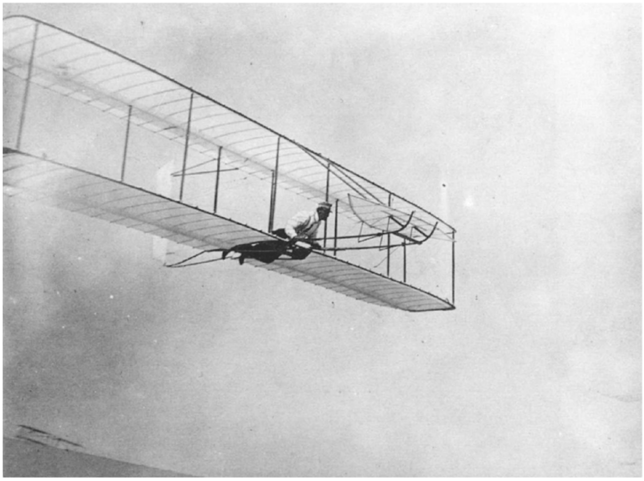

Figure 1.2 1902 Wright Glider featuring lateral and directional control by warping. Reproduced by permission of United States Air Force Historical Research Agency

Correctly recognizing that achieving harmony of control would greatly improve the control and usefulness of an aircraft, in October 1902 the Wrights developed an interconnection between warping of the wing and warping of the vertical tail. Thus the concept of what would later become the aileron-to-rudder interconnect or ARI was born. With the problems of longitudinal control, lateral control, directional control, and control harmony solved, the 1902 Wright Glider became essentially the world's first successful airplane (Crouch 1989). These developments paved the way for the success of the powered 1903 Wright Flyer a year later.

The Etrich Taube ("dove" in German) series of designs have probably been the ultimate expression of bio-inspiration to aircraft design. In fact, except for the omission of flapping wings, the Taube designs are essentially bio-mimetic, i.e. directly mimicking a biological system (Figure 1.3). The Etrich Luft-Limousine / VII was somewhat unique for an airplane of

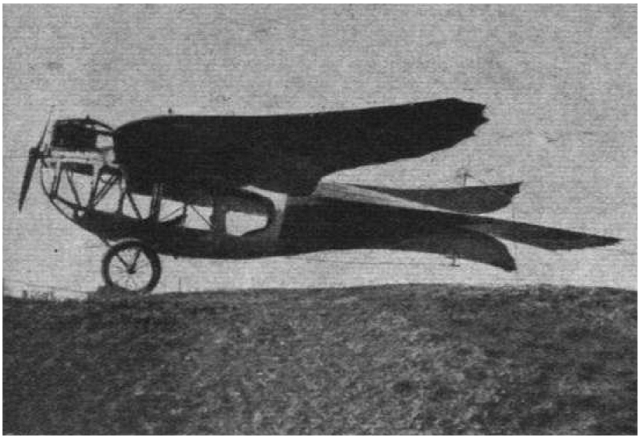

Figure 1.3 Etrich Luft-Limousine / VII four-seater passenger airplane of 1912

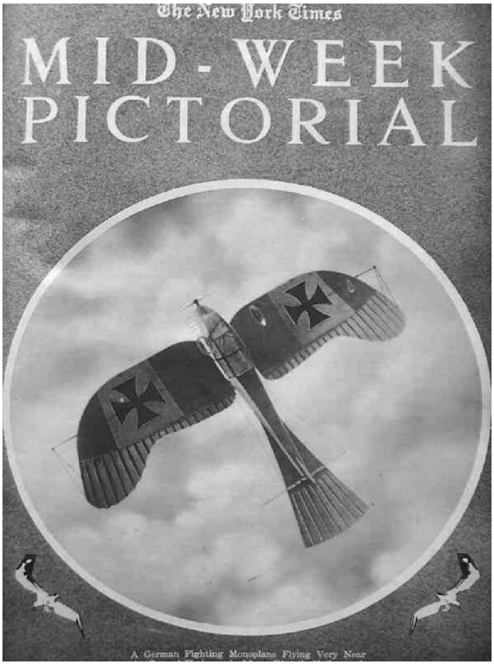

Figure 1.4 Rumpler Taube on the front page of the *New York Times Mid-Week Pictorial*, January 1st, 1917

its time since it employed multi-material construction. This consisted of an aluminum sheet covering from the nose to just behind the wings, with wood used everywhere else. The fuselage structure used wooden rings and channel-section longitudinal members and the windows were celluloid and wire gauze. The initial Taube designs were created by Igo Etrich in Austria in 1909. The original inspiration for the unique wing planform on Taube designs was not a bird wing, but the Zanonia macrocarpa seed, which falls from trees in a slow spin induced by a single wing. This was not successful, yet the influence of birds on later adaptations of this wing design can clearly be seen (Figure 1.4). Like the Wright designs, the Taube designs employed wing and horizontal tail warping via wires and external posts, although the vertical tail surfaces were hinged. Despite contemporary aircraft designs which featured vertical tails of a size and proportion that would be recognizable in modern designs, the Taube designs mimicked birds so much that the dorsal and ventral fins comprising the vertical tail surfaces were very small. Ultimately, the very small vertical tail surfaces became a distinguishing characteristic of the Taube designs.

The Wright and Taube designs demonstrated that warping controls can be effective on aircraft with thin and flexible wings. But the invention of the now conventional hinged controls, such as ailerons and rudders, was essential for later aircraft with more rigid structures and metallic materials. Thus the problem of materials and structures has been a central consideration to morphing aircraft from the outset. By the onset of the First World War in 1914 and in the years afterward, virtually all high performance aircraft used conventional hinged control surfaces instead of warping. With the advent of aircraft with relatively rigid metallic structures in the 1930s, the path to morphing clearly lay in changing the geometry of the aircraft via complex arrangements of conventional hinges, pivots, and rails rather than warping.

1.3 The Middle Years: Variable Geometry

During the inter-war years in France, Ivan Makhonine conceived the idea of a telescoping wing aircraft. The aim was to improve cruise performance by reducing the induced drag, or the drag due to the creation of lift. This was to be accomplished by reducing span loading which is the ratio of aircraft weight to wing span. As shown in Figure 1.5, the mechanism

Figure 1.5 The Makhonine MAK-101 telescoping wing airplane of 1933: wing tip extended (top) and retracted (bottom)

Figure 1.6 Sir Barnes Neville Wallis with a model of the Swallow, wings at low sweep

works like a stiletto knife, except that the wing can also be retracted automatically since it was pneumatically powered with a standby manual system. The fixed landing gear MAK-10 was first flown in 1931, followed by the retractable landing gear MAK-101 in 1933. The MAK-101 was flown many times over the next several years until it was destroyed in its hangar during a USAAF bombing raid late in the Second World War. Makhonine continued his research into the telescoping wing concept post-war, culminating in the last aircraft in the series, the MAK-123 which first flew in 1947. The MAK-123 was a four-seat passenger aircraft that flew well and was reported to have adequate handling qualities, but was damaged in a forced landing and never flew again.

British aircraft designer Sir Barnes Neville Wallis, well known as the inventor of the geodesic structural design concept used in the Vickers Wellington medium bomber, also investigated novel variable geometry configurations. Although he did not invent the swing-wing concept, Wallis devoted much effort to making what he called the "wing-controlled aerodyne" practical as a means of achieving supersonic flight. His two main goals were to use variable geometry as a solution to handling the center of gravity changes during flight, and to achieve laminar flow over the wing body. His Wild Goose design of the 1940s was a military mission supersonic concept with a slender laminar flow body and swing-wings. Several sub-scale models of the Wild Goose were successfully flown in the late 1940s and early 1950s. A full-scale piloted version of the Wild Goose was planned but later cancelled in 1952. The Swallow was a longer-range derivative of the Wild Goose, designed in the 1950s. Many sub-scale models were produced (Figure 1.6) and flown, and the results were so promising that full-scale versions were planned. However, these were not to be implemented due to the British defense funding climate of the late 1950s. Nevertheless, the Swallow was influential as a military concept

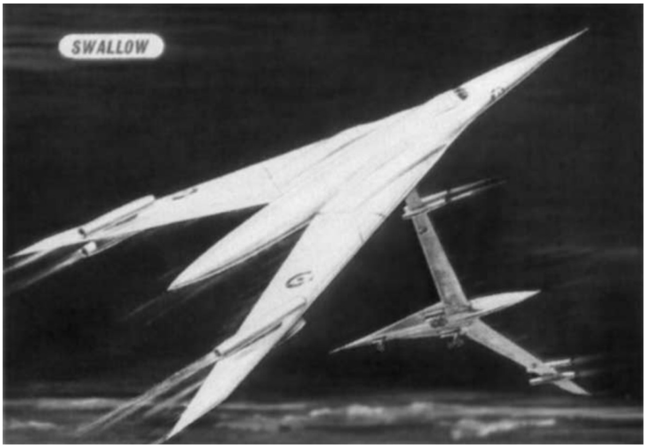

Figure 1.7 An illustration of the Swallow by Barnes Wallis

aircraft (Figure 1.7) and inspired various design features which later appeared in U.S. aircraft such as the General Dynamics F-111 Aardvark. During this same period in the USA, variable geometry research sponsored by NASA paved the way for experimental transonic designs such as the Bell X-5 (Figure 1.8). The X-5 was the first full-scale aircraft to be flown which was capable of sweeping its wings in flight. The wing sweep angles could be set in flight to 20, 45, and 60 degrees and were tested at subsonic and transonic speeds. With the wings fully extended, the low-speed performance was improved for take-off and landing, and with the wings swept back, the high speed performance was improved and drag was reduced. Results of this research directly influenced the design of the General Dynamics F-111 Aardvark and the Grumman F-14 Tomcat, both of which went into large-scale production. It is interesting

Figure 1.8 Bell X-5 showing variable sweep wing positions. Reproduced by permission of National Aeronautics and Space Administration

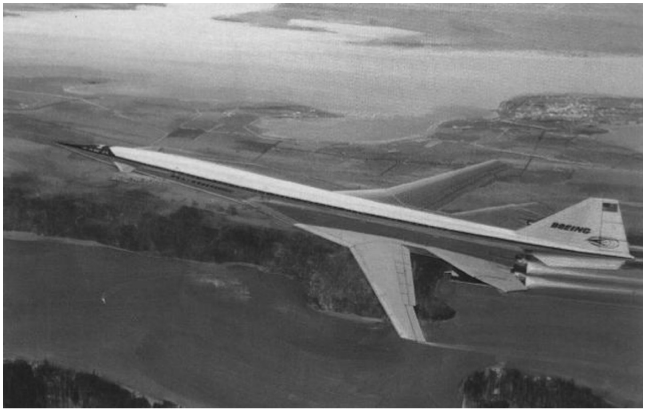

Figure 1.9 Boeing 2707 Supersonic Transport notional configuration with variable sweep wing

to note that the variable geometry concept eventually found its way into the commercial air transport sector as well. It was seriously considered for various conceptual designs, including the Boeing 2707 Supersonic Transport of the 1960s (Figure 1.9). Even though the B2707 never progressed beyond the full-scale mock-up stage, a large variable geometry supersonic aircraft appeared a decade later in the form of the Rockwell International B-1A bomber. NASA later conducted a research program with an aircraft that combined *both* variable geometry and shape changing similar to the traditional wing warping of the early pioneers. The AFTI F-111 Mission Adaptive Wing (MAW), shown in Figure 1.10, was intended to minimize penalties for off-design flight conditions through a combination of smooth-skin variable camber and variable wing sweep angle. As opposed to the hinged flaps with discontinuous surfaces and exposed mechanisms of conventional aircraft, the variable camber surfaces of the MAW feature smooth flexible upper surfaces and fully enclosed lower surfaces that can be actuated in flight to provide the desired wing camber. This flight research program was highly successful and served as a vital stepping stone toward the realization of a fully morphing aircraft.

With all of the successes of the variable geometry approach, it is not surprising that bio-inspiration was largely overlooked or simply not considered promising enough during this

Figure 1.10 NASA AFTI F-111 Mission Adaptive Wing. Reproduced by permission of National Aeronautics and Space Administration