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Introduction

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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.

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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.

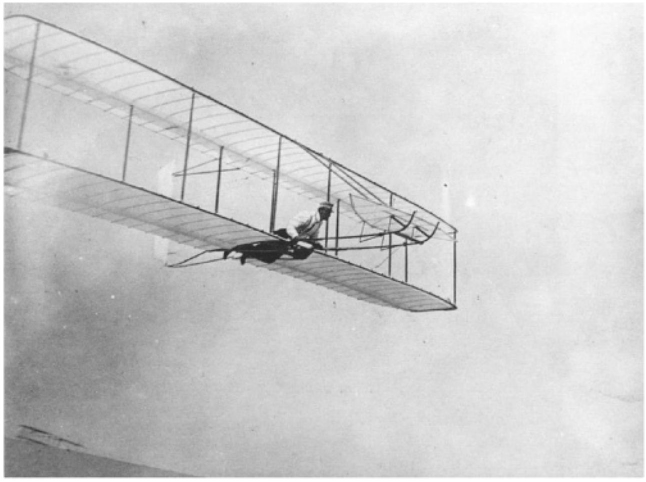

Figure 1.2 1902 Wright Glider featuring lateral and directional control by warping. Reproduced by permission of United States Air Force Historical Research Agency

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

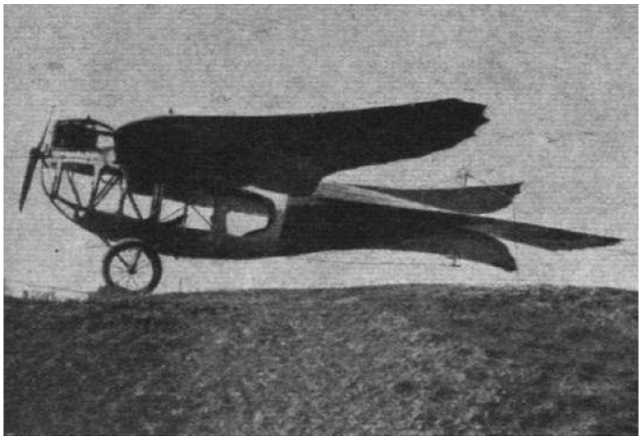

Figure 1.3 Etrich Luft-Limousine / VII four-seater passenger airplane of 1912

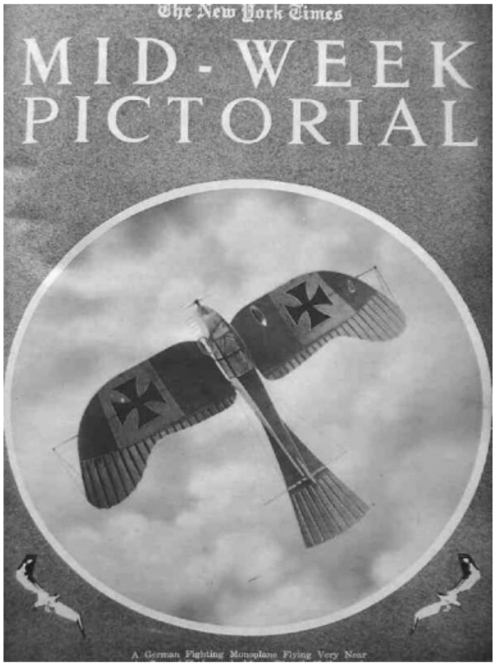

Figure 1.4 Rumpler Taube on the front page of the *New York Times Mid-Week Pictorial*, January 1st, 1917

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


Premier prototype d'avion à géométrie variable de Makhonine - Archives B et J Soarès

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

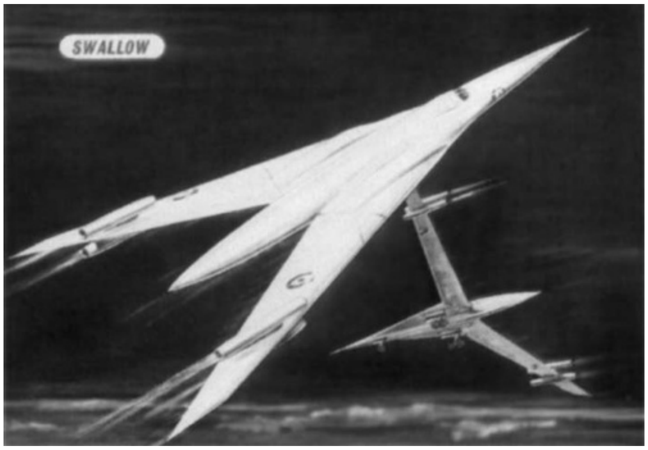

Figure 1.7 An illustration of the Swallow by Barnes Wallis

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

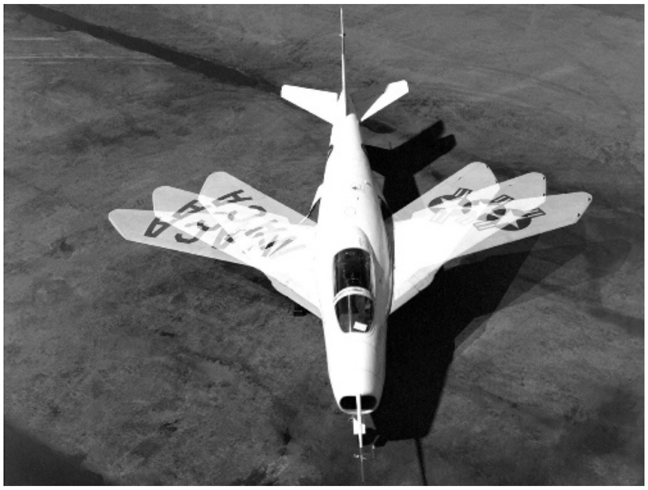

Figure 1.8 Bell X-5 showing variable sweep wing positions. Reproduced by permission of National Aeronautics and Space Administration

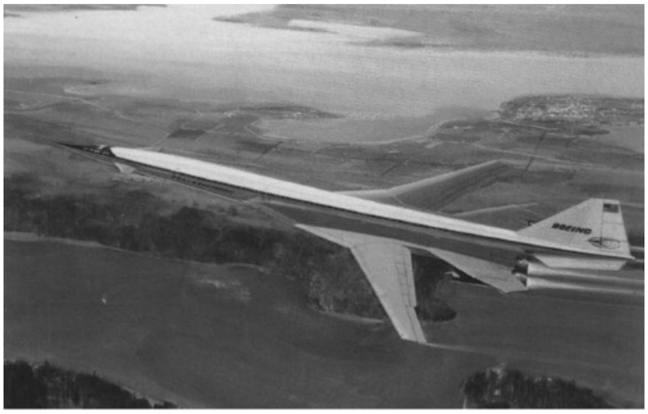

Figure 1.9 Boeing 2707 Supersonic Transport notional configuration with variable sweep wing

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

period. John Harris opined in 1989 the feelings of some that "(Yet) birds are terrible models for human flight, and a too slavish attention to their example – often unconscious – has often impeded the development of aircraft. An airplane is not a bird, and designers throughout the history of aircraft development have had a hard time fully realizing this (Harris 1989)." In spite of this, a dramatic change in the way morphing aircraft were viewed was about to take place.

1.4 The Later Years: A Return to Bio-Inspiration

Recent discoveries in bird flight mechanics and new insights for bio-inspiration led many researchers to reconsider birds as models for morphing aircraft. Two significant and ambitious research programs that were to have far-reaching and productive effects on morphing aircraft appeared nearly simultaneously around 2000. The NASA Morphing Aircraft Project was a large and highly coordinated program conducted from 1994–2004 (Wlezien et al. 1998). It was a wide-ranging, large scope program that was specifically targeted at high pay-off applications that would enable efficient, multi-point adaptability aircraft and spacecraft. In the context of the project, the word "morphing" was defined as "efficient, multi-point adaptability" and could include macro, micro, structural and/or fluidic approaches. This program enabled and sponsored research across a broad range of technologies that included biotechnology, nanotechnology, biomaterials, adaptive structures, micro-flow control, biomimetic concepts, optimization, and controls. At its height this program supported between 80 to 100 researchers. The focal point for all technologies in this program was the notional NASA morphing unmanned air vehicle shown in Figure 1.11. This aircraft brought together most of the earlier morphing concepts, including bio-inspiration, warping, shape-changing, variable geometry, structures, materials, controls, and aerodynamics. Most importantly, it sought to address the contribution of propulsion in a fully integrated fashion. This notional aircraft continues to serve as useful concept and model for morphing research.

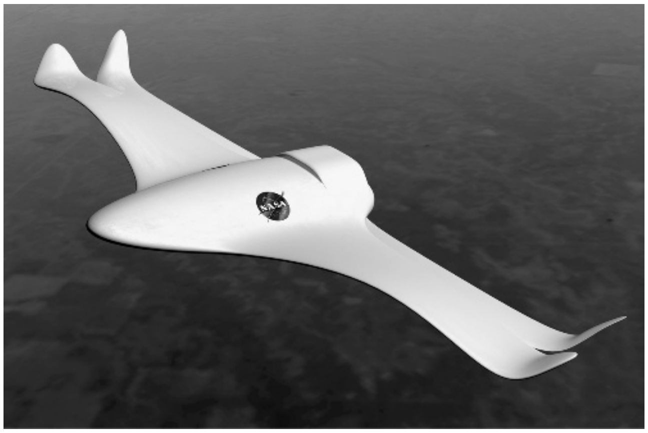

Figure 1.11 NASA morphing unmanned air vehicle concept. Reproduced by permission of National Aeronautics and Space Administration

The DARPA Morphing Aircraft Structures (MAS) Program dates back to 2002 and continued until 2007. The Defense Technology Directive stated that:

> Morphing is a capability to provide superior and/or new vehicle system performance while in flight by tailoring the vehicle's state to adapt to the external operational environment and multi-variable mission roles. In the context of this DTO, morphing aircraft are multi-role aircraft that change their external shape substantially to adapt to a changing mission environment during flight
>
> — (Anonymous 2006)

The DARPA Morphing Aircraft Structures Program responded to this DTO with objectives defined as the design and fabrication of effective combinations of integrated wing skins, actuators and mechanisms, structures, and flight controls to achieve the anticipated diverse, conflicting aircraft mission capabilities via wing shape change. For a notional aircraft, the DARPA/MAS program used a so-called Hunter-Killer unmanned aircraft concept that combined reconnaissance aircraft features of aircraft like the General Atomics Predator or Northrop Grumman Global Hawk, with the attack features of a fast attack aircraft such as the General Dynamics F-16. Studies indicated that morphing wings would enable multi-functional Hunter-Killer mission features such as: (1) responsiveness – time-critical ability to respond to unpredictable crisis situations; (2) agility – the ability to change system roles on demand; and (3) persistence – the ability to dominate large operational areas for long time periods. The DARPA/MAS program generated many useful results and insights, and culminated in the flight test of a small demonstrator.

1.5 Conclusion

This chapter has related the main historical research and development path of the morphing air vehicle, along the way highlighting key ideas and connections between bio-inspiration and aeronautical engineering. Over the course of these developments, it is clear that ideas which were once old are new again. The following chapters in this book tell the contemporary story of the morphing air vehicle in three parts: Part I Bio-inspiration, Part II Control and Dynamics, and Part III Smart Materials and Structures. The volume concludes with a discussion of current and future challenges, and a look at the way forward.

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