NASA'S CONTRIBUTIONS TO AERONAUTICS

VOLUME 1

AERODYNAMICS
STRUCTURES
PROPULSION
CONTROLS

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AERONAUTICS

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Contents

Foreword

AS THIS BOOK GOES TO PRESS, the National Aeronautics and Space Administration (NASA) has passed beyond the half century mark, its longevity a tribute to how essential successive Presidential administrations—and the American people whom they serve—have come to regard its scientific and technological expertise. In that half century, flight has advanced from supersonic to orbital velocities, the jetliner has become the dominant means of intercontinental mobility, astronauts have landed on the Moon, and robotic spacecraft developed by the Agency have explored the remote corners of the solar system and even passed into interstellar space.

Born of a crisis—the chaotic aftermath of the Soviet Union's space triumph with Sputnik—NASA rose magnificently to the challenge of the emergent space age. Within a decade of NASA's establishment, teams of astronauts would be planning for the lunar landings, first accomplished with Neil Armstrong's "one small step" on July 20, 1969. Few events have been so emotionally charged, and none so publicly visible or fraught with import, as his cautious descent from the spindly little Lunar Module Eagle to leave his historic boot-print upon the dusty plain of Tranquillity Base.

In the wake of Apollo, NASA embarked on a series of space initiatives that, if they might have lacked the emotional and attention-getting impact of Apollo, were nevertheless remarkable for their accomplishment and daring. The Space Shuttle, the International Space Station, the Hubble Space Telescope, and various planetary probes, landers, rovers, and flybys speak to the creativity of the Agency, the excellence of its technical personnel, and its dedication to space science and exploration.

But there is another aspect to NASA, one that is too often hidden in an age when the Agency is popularly known as America's space agency and when its most visible employees are the astronauts who courageously rocket into space, continuing humanity's quest into the unknown. That hidden aspect is aeronautics: lift-borne flight within the atmosphere, as distinct from the ballistic flight of astronautics, out into space. It is the first "A" in the Agency's name and the oldest-rooted of the Agency's technical competencies, dating to the formation, in 1915, of NASA's lineal predecessor, the National Advisory Committee for Aeronautics (NACA). It was the NACA that largely restored America's aeronautical primacy in the interwar years after 1918, deriving the airfoil profiles and configuration concepts that defined successive generations of ever-more-capable aircraft as America progressed from the subsonic piston era into the transonic and supersonic jet age. NASA, succeeding the NACA after the shock of Sputnik, took American aeronautics across the hypersonic frontier and onward into the era of composite structures, electronic flight controls, and energy-efficient flight.

This volume, the first of a two-volume set, traces contributions by NASA and the post–Second World War NACA to the field of aeronautics. It was that work that enabled the exploitation of the turbojet and high-speed aerodynamic revolution that led to the gas-turbine-powered jet age that followed, within which we still live. The subjects covered in this first volume are an eclectic mix of surveys, case studies, and biographical examinations ranging across multiple disciplines and technical competencies residing within the National Aeronautics and Space Administration. The topics are indicative of the range of Agency work and the capabilities of its staff. They include:

- The advent of the sharply swept-back wing, which enabled taking fullest advantage of the turbojet revolution and thereby launched the era of high-speed global mass mobility, becoming itself the iconic symbol of the jet age.
- The contributions and influence of Richard T. Whitcomb, a legendary NACA–NASA researcher who gave to aeronautics some of the key methods of reducing drag and improving flight efficiencies in the challenging transonic region, between subsonic and supersonic flight.
- The work of the NACA and NASA in furthering the rotary wing revolution via research programs on a range of rotorcraft from autogiros through helicopters, convertiplanes, ducted fan, tilt wing, and tilt rotor craft.

- How NASA worked from the earliest days of the supersonic revolution to mitigate the shock and disturbing effects of the sonic boom, developing creative test approaches to evaluate boom noise and overpressures, and then methods to alleviate boom formation and impingement, leading to novel aircraft shaping and methods that are today promising to revolutionize the design of transonic and supersonic civil and military aircraft.
- How the NACA and NASA, having mastered the transonic and supersonic regions, took on the challenge of extending lift-borne flight into the hypersonic region and thence into space, using exotic "transatmospheric" vehicles such as the legendary X-15, various lifting bodies, and the Space Shuttle, and extending the frontiers of air-breathing propulsion with the Mach 9+ scramjet-powered X-43.
- The physical problems and challenges that forced NASA and other researchers to study and find pragmatic solutions for such thorny issues as aeroelasticity, oscillatory instabilities forcing development of increasingly sophisticated artificial stability systems, flight simulation for high-performance aerospace vehicles, and aerothermodynamic structural deformation and heating.
- NASA's role in advancing and maturing computational fluid dynamics (CFD) and applying this new tool to aeronautical research and aerospace vehicle design.
- The exploitation of materials science and development of high-temperature structures to enable design of practical high-speed military and civil aircraft and spacecraft.
- The advent of computerized structural loads prediction, modeling, and simulation, which, like CFD, revolutionized aerospace design practices, enhancing both safety and efficiency.
- NASA's pioneering of electronic flight control ("fly-by-wire"), from rudimentary testbeds evolved from Apollo-era computer architectures and software, to increasingly sophisticated systems integrating aerodynamic and propulsion controls.

- How the NACA and NASA advanced the gas turbine revolution, producing more efficient engine concepts and technology for application to new generations of military and civilian aircraft.
- How NASA has contributed to the quest for fuel-efficient and environmentally friendly aircraft technology, studying combustion processes, alternative fuels, and pollutant transfer into the upper atmosphere, searching for appropriate technological solutions, and resulting in less polluting, less wasteful, and more efficient aircraft designs.
- The Agency's work in promoting global environmental good stewardship by applying its scientific and technical competencies to wind and solar energy, resulting in more efficient energy-producing wind turbines and high-altitude solar-powered long-endurance unpiloted aerial vehicles.

The record of NACA–NASA accomplishments in aeronautics demonstrates the value of consistent investment in aeronautical research as a means of maintaining the health and stability of America's aerospace industrial base. That base has generated an American predominance in both civil and military aeronautics, but one that is far from assured as the Nation enters the second century of winged flight. It is hoped that these studies, offering a glimpse at the inner workings of the Agency and its personnel, will prove of value to the men and women of NASA, to those who benefit across the United States and overseas from their dedicated work, and to students of aeronautics and members of the larger aerospace community. It is to the personnel of NASA, and the NACA before them, that this volume is dedicated, with affection and respect.

Dr. Richard P. Hallion
August 4, 2010

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The X-48B subscale demonstrator for the Blended Wing-Body (BWB). The BWB may represent the next extension of the swept and delta wing, to transform flight away from the rule of the "tube and wing" jetliner. NASA.

CASE 1

Sweep and Swing: Reshaping the Wing for the Jet and Rocket Age

Richard P. Hallion

The development of the swept and delta wing planform enabled practical attainment of the high speeds promised by the invention of the turbojet engine and the solid-and-liquid-fueled rocket. Refining the swept and delta planforms from theoretical constructs to practical realities involved many challenges and problems requiring creative analysis and study by NACA and NASA researchers. Their insight and perseverance led to the swept wing becoming the iconic symbol of the jet age.

THE PROGRESSIVE EVOLUTION OF AIRCRAFT DESIGN HAS WITNESSED continuous configuration changes, adaptations, and reinterpretations. The canard wood-and-fabric biplane launched the powered flight revolution and gave way to the tractor biplane and monoplane, and both gave way to the all-metal monoplane of the interwar era. The turbojet engine set aside the piston engine as the primary motive power for long-range commercial and military aircraft, and it has been continually refined to generate the sophisticated bypass turbofans of the present era, some with afterburning as well. The increasing airspeed of aircraft drove its own transformation of configuration, measurable in the changed relationship between aspect and fineness ratios. Across the primacy of the propeller-driven era, from the beginning of the 20th century to the end of the interwar era, wingspan generally far exceeded fuselage length. That changed early in the jet and rocket era. By the time military and test pilots from the National Advisory Committee for Aeronautics (NACA) first probed the speed of sound with the Bell XS-1 and Douglas D-558-1 Skystreak, wingspan and fuselage length were roughly equal. Within a decade, as aircraft speed extended into the supersonic regime, the ratio of wingspan to fuselage length dramatically reversed, evidenced by aircraft such as the Douglas X-3, the Lockheed F-104 Starfighter, and the Anglo-French Concorde Supersonic Transport (SST). Nicknames handily captured the transformation: the rakish X-3 was known informally as the "Stiletto" and the only slightly less sleek F-104 as the "Missile with a Man in It."

There was as well another manifestation of profound design transformation, one that gave to the airplane a new identity that swiftly became a global icon: the advent of the swept wing. If the biplane constituted the normative airplane of the first quarter century of flight and the straight wing cantilever monoplane that of the next quarter century, by the time of the golden anniversary of Kitty Hawk, the swept wing airplane had supplanted both, its futuristic predominance embodied by the elegant North American F-86 Sabre that did battle in "MiG Alley," high over North Korea's blue-gray hills bordering the Yalu River. In the post-Korean era, as swept wing Boeing 707 and Douglas DC-8 jet airliners replaced what historian Peter Brooks termed the "DC-4 generation" of straight wing propeller-driven transports, the swept wing became the iconic embodiment of the entire jet age.[1] Today, 75 years since its enunciation at an international conference, the high-speed swept wing is the commonly accepted global highway symbol for airports, whether an intercontinental center such as Los Angeles, Frankfurt, or Heathrow; regional hubs such as Dallas, Copenhagen, or Charlotte; or any of the myriad general aviation and business aviation airfields around the world, even those still primarily populated, ironically, by small, straight wing propeller-and-piston-driven airplanes.

The Tailless Imperative: The Early History of Swept and Delta Wings

The high-speed swept wing first appeared in the mid-1930s and, like most elements in aircraft design, was European by birth. But this did not mark the swept wing's first appearance in the world's skies. The swept wing dated to before the First World War, when John Dunne had developed a series of tailless flying wing biplanes using the swept planform as a means of ensuring inherent longitudinal stability, imparting "self-correcting" restoration of any gust-induced pitching motions. Dunne's aircraft, while freakish, did enjoy some commercial success. He sold manufacturing

1. Peter W. Brooks, *The Modern Airliner: Its Origins and Development* (London: Putnam & Co., Ltd., 1961), pp. 91–111. Brooks uses the term to describe a category of large airliner and transport aircraft defined by common shared design characteristics, including circular cross-section constant-diameter fuselages, four-engines, tricycle landing gear, and propeller-driven (piston and turbo-propeller), from the DC-4 through the Bristol Britannia, and predominant in the time period 1942 through 1958. Though some historians have quibbled with this, I find Brooks's reasoning convincing and his concept of such a "generation" both historically valid and of enduring value.

rights to the Burgess Company in the United States, which subsequently produced two "Burgess-Dunne" seaplanes for the U.S. Navy. Lt. Holden C. Richardson, subsequently one of the first members of the NACA, had urged their purchase "so that the[ir] advantages and limitations can be thoroughly determined . . . as it appears to be only the beginning of an important development in aeronautical design."[2]

That it was, though not in the fashion Richardson expected. The swept wing remained an international staple of tailless self-stabilizing design, typified in the interwar years by the various Westland Pterodactyl aircraft designed by Britain's G.T.R. Hill, the tailless aircraft of Boris Ivanovich Cheranovskiy, Waldo Waterman's Arrowplane, and a series of increasingly sophisticated sailplanes and powered aircraft designed by Germany's Alexander Lippisch. However, it would not become the "mainstream" element of aircraft design its proponents hoped until applied to a very different purpose: reducing transonic aerodynamic effects.[3] The transonic swept wing effectively increased a wing's critical Mach number (the "drag divergence Mach number"), delaying the onset of transonic drag rise and enabling an airplane to fly at higher transonic and supersonic speeds for the same energy expenditure and drag penalty that a straight wing airplane would expend and experience at much lower subsonic speeds.

In 1935, leading aerodynamicists gathered in Rome for the Volta Congress on High Speeds in Aviation, held to coincide with the opening of Italy's impressive new Guidonia laboratory complex. There, a young German fluid dynamicist, Adolf Busemann, unveiled the concept of using the swept wing as a means of attaining supersonic flight.[4] In his presentation, he

2. Quoted in Roy A. Grossnick, et al., *United States Naval Aviation 1910–1995* (Washington: U.S. Navy, 1997), p. 15; Gordon Swanborough and Peter M. Bowers, *United States Navy Aircraft Since 1911* (New York: Funk & Wagnalls, 1968), p. 394.

3. Alexander Lippisch, "Recent Tests of Tailless Airplanes," NACA TM-564 (1930), a NACA translation of his article *"Les nouveaux essays d'avions sans queue," l'Aérophile* (Feb. 1–15, 1930), pp. 35–39.

4. For Volta, see Theodore von Kármán and Lee Edson, *The Wind and Beyond: Theodore von Kármán, Pioneer in Aviation and Pathfinder in Space* (Boston: Little, Brown and Co., 1967), pp. 216–217, 221–222; Adolf Busemann, "Compressible Flow in the Thirties," *Annual Review of Fluid Mechanics*, vol. 3 (1971), pp. 6–11; Carlo Ferrari, "Recalling the Vth Volta Congress: High Speeds in Aviation," *Annual Review of Fluid Mechanics*, vol. 28 (1996), pp. 1–9; Hans-Ulrich Meier, "Historischer Rückblick zur Entwicklung der Hochgeschwindigkeitsaerodynamik," in H.-U. Meier, ed., *Die Pfeilflügelentwicklung in Deutschland bis 1945* (Bonn: Bernard & Graefe Verlag, 2006), pp. 16–36; and Michael Eckert, *The Dawn of Fluid Dynamics: A Discipline Between Science and Technology* (Weinheim: Wiley-VCH Verlag, 2006), pp. 228–231.

demonstrated the circulation pattern around a swept wing that, essentially, "fooled" it into "believing" it was flying at lower velocities. As well, he presented a sketch of an aircraft with such a "Pfielförmiges Tragwerk" ("Arrow-Shaped Lifting Surface"), though one that had, by the standards of subsequent design, very modest sweep and very high aspect ratio.[5]

Theodore von Kármán recalled not quite two decades later that afterward, at the conference banquet, "General [Arturo] Crocco, the organizer of the congress and a man of far-reaching vision, went further while doodling on the back of the menu card, drawing a plane with swept-back wings and tail, and even swept propeller blades, laughingly calling it 'Busemann's airplane.'"[6] Evidence exists that Crocco took the concept beyond mere dinner conversation, for afterward, Guidonia researchers evaluated a design blending modestly swept wings with a "push-pull" twin-engine fuselage configuration. However, Guidonia soon returned to the more conventional, reflecting the Italian air ministry's increasing emphasis upon building a large and powerful air arm incorporating already proven and dependable technology.[7]

Delegates from other nations present at Busemann's briefing missed its significance altogether, perhaps because his gently swept configuration—in the era of the DC-2 and DC-3, which had pronounced leading edge taper—looked far less radical than the theory and purpose behind it implied. NACA Langley Memorial Aeronautical Laboratory researchers had already evaluated far more sharply swept planforms at Langley for a seminal wing taper study the laboratory issued the next year.[8] Thus, at first glance, Busemann's design certainly did not look like a shape that would transform aviation from the firmly subsonic to the transonic, making possible the potential of the jet engine, and the jet age (with its jet set) that followed.

5. Adolf Busemann, "Aerodynamische Auftrieb bei Überschallgeschwindigkeit," *Luftfahrtforschung*, vol. 12, No. 6 (Oct. 3, 1935), pp. 210–220, esp. Abb. 4–5 (Figures 4–5).
6. Theodore von Kármán, *Aerodynamics* (New York: McGraw-Hill Book Company, Inc., 1963 ed.), p. 133.
7. Ministero dell'Aeronautica, 1° Divisione, *Sezione Aerodinamica Resultati di Esperienze* (Rome: Guidonia, 1936); the swept "double-ender" wind tunnel study (anticipating the layout of Dornier's Do 335 *Pfeil* ["Arrow"] of the late wartime years) was designated the J-10; its drawing is dated March 7, 1936. I thank Professor Claudio Bruno of the Università degli Studi di Roma "La Sapienza"; and Brigadier General Marcello di Lauro and Lieutenant Colonel Massimiliano Barlattani of the Stato Maggiore dell'Aeronautica Militare (SMdAM), Rome, for their very great assistance in enabling me to examine this study at the Ufficio Storico of the SMdAM in June 2009.
8. Raymond F. Anderson, "Determination of the Characteristics of Tapered Wings," NACA Report No. 572 (1936); see in particular Figs. 15 and 16, p. 11.