NASA'S CONTRIBUTIONS TO AERONAUTICS

VOLUME 2

FLIGHT ENVIRONMENT

OPERATIONS

FLIGHT TESTING AND RESEARCH

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Fax: (202) 512-2104 Mail: Stop IDCC, Washington, DC 20402-0001

ISBN 978-0-16-084636-6

ISBN 978-0-16-084636-6

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2010

NASA/SP-2010-570-Vol 2

www.nasa.gov

Library of Congress Cataloging-in-Publication Data

NASA's contributions to aeronautics : aerodynamics, structures, propulsion, and controls / Richard P. Hallion, editor.
v. cm.
Includes bibliographical references and index.
"NASA/SP-2010-570."
1. United States. National Aeronautics and Space Administration--History. 2. Aeronautics--Research--United States--History. I. Hallion, Richard.

TL521.312.N3825 2010
629.130973--dc22

2009044645

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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 first lunar landings, 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.

As with the first in this series, this second volume traces contributions by NASA and the post–Second World War NACA to aeronautics. The surveys, cases, and biographical examinations presented in this work offer just a sampling of the rich legacy of aeronautics research having been produced by the NACA and NASA. These include

- Atmospheric turbulence, wind shear, and gust research, subjects of crucial importance to air safety across the spectrum of flight, from the operations of light general-aviation aircraft through large commercial and supersonic vehicles.
- Research to understand and mitigate the danger of lightning strikes upon aerospace vehicles and facilities.
- The quest to make safer and more productive skyways via advances in technology, cross-disciplinary integration of developments, design innovation, and creation of new operational architectures to enhance air transportation.
- Contributions to the melding of human and machine, via the emergent science of human factors, to increase the safety, utility, efficiency, and comfort of flight.
- The refinement of free-flight model testing for aerodynamic research, the anticipation of aircraft behavior, and design validation and verification, complementing traditional wind tunnel and full-scale aircraft testing.

- The evolution of the wind tunnel and expansion of its capabilities, from the era of the slide rule and subsonic flight to hypersonic excursions into the transatmosphere in the computer and computational fluid dynamics era.
- The advent of composite structures, which, when coupled with computerized flight control systems, gave aircraft designers a previously unknown freedom enabling them to design aerospace vehicles with optimized aerodynamic and structural behavior.
- Contributions to improving the safety and efficiency of general-aviation aircraft via better understanding of their unique requirements and operational circumstances, and the application of new analytical and technological approaches.
- Undertaking comprehensive flight research on sustained supersonic cruise aircraft—with particular attention to their aerodynamic characteristics, airframe heating, use of integrated flying and propulsion controls, and evaluation of operational challenges such as inlet "unstart," aircrew workload—and blending them into the predominant national subsonic and transonic air traffic network.
- Development and demonstration of Synthetic Vision Systems, enabling increased airport utilization, more efficient flight deck performance, and safer air and ground aircraft operations.
- Confronting the persistent challenge of atmospheric icing and its impact on aircraft operations and safety.
- Analyzing the performance of aircraft at high angles of attack and conducting often high-risk flight-testing to study their behavior characteristics and assess the value of developments in aircraft design and flight control technologies to reduce their tendency to depart from controlled flight.
- Undertaking pathbreaking flight research on VTOL and V/STOL aircraft systems to advance their ability to enter the mainstream of aeronautical development.
- Conducting a cooperative international flight-test program to mutually benefit understanding of the potential, behavior, and performance of large supersonic cruise aircraft.

As this sampling—far from a complete range—of NASA work in aeronautics indicates, the Agency and its aeronautics staff spread across the Nation maintain a lively interest in the future of flight, benefitting NASA's reputation earned in the years since 1958 as a national repository of aerospace excellence and its legacy of accomplishment in the 43-year history of the National Advisory Committee for Aeronautics, from 1915 to 1958.

As America enters the second decade of the second century of winged flight, it is again fitting that this work, like the volume that precedes it, be dedicated, with affection and respect, to the men and women of NASA, and the NACA from whence it sprang.

Dr. Richard P. Hallion
August 25, 2010

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NASA 515, Langley Research Center's Boeing 737 testbed, is about to enter a microburst wind shear. The image is actual test footage, reflecting the murk and menace of wind shear. NASA.

CASE 1

Eluding Aeolus: Turbulence, Gusts, and Wind Shear

Kristen Starr

Since the earliest days of American aeronautical research, NASA has studied the atmosphere and its influence upon flight. Turbulence, gusts, and wind shears have posed serious dangers to air travelers, forcing imaginative research and creative solutions. The work of NASA's researchers to understand atmospheric behavior and NASA's derivation of advanced detection and sensor systems that can be installed in aircraft have materially advanced the safety and utility of air transport.

BEFORE WORLD WAR II, the National Advisory Committee for Aeronautics (NACA), founded in 1915, performed most of America's institutionalized and systematic aviation research. The NACA's mission was "to supervise and direct the scientific study of the problems of flight with a view to their practical solution." Among the most serious problem it studied was that of atmospheric turbulence, a field related to the Agency's great interest in fluid mechanics and aerodynamics in general. From the 1930s to the present, the NACA and its successor—the National Aeronautics and Space Administration (NASA), formed in 1958—concentrated rigorously on the problems of turbulence, gusts, and wind shear. Midcentury programs focused primarily on gust load and boundary-layer turbulence research. By the 1980s and 1990s, NASA's atmospheric turbulence and wind shear programs reached a level of sophistication that allowed them to make significant contributions to flight performance and aircraft reliability. The aviation industry integrated this NASA technology into planes bought by airlines and the United States military. This research has resulted in an aviation transportation system exponentially safer than that envisioned by the pioneers of the early air age.

An Unsettled Sky

When laypeople think of the words "turbulence" and "aviation" together, they probably envision the "bumpy air" that passengers are often subjected to on long-duration plane flights. But the term "turbulence" has a particular technical meaning. Turbulence describes the motion of a fluid (for, our purposes, air) that is characterized by chaotic, seemingly random property changes. Turbulence encompasses fluctuations in diffusion, convection, pressure, and velocity. When an aircraft travels through air that experiences these changes, its passengers feel the turbulence buffeting the aircraft. Engineers and scientists characterize the degree of turbulence with the Reynolds number, a scaling parameter identified in the 1880s by Osborne Reynolds at the University of Manchester. Lower numbers denote laminar (smooth) flows, intermediate values indicate transitional flows, and higher numbers are characteristic of turbulent flow.[1]

A kind of turbulent airflow causes drag on all objects, including cars, golf balls, and planes, which move through the air. A boundary layer is "the thin reaction zone between an airplane [or missile] and its external environment." The boundary layer is separated from the contour of a plane's airfoil, or wing section, by only a few thousandths of an inch. Air particles change from a smooth laminar flow near the leading edge to a turbulent flow toward the airfoil's rear.[2] Turbulent flow increases friction on an aircraft's skin and therefore increased surface heat while slowing the speed of the aircraft because of the drag it produces.

Most atmospheric circulation on Earth causes some kind of turbulence. One of the more common forms of atmospheric turbulence experienced by aircraft passengers is clear air turbulence (CAT), which is caused by the mixing of warm and cold air in the atmosphere by wind, often via the process of wind shear. Wind shear is a difference in wind speed and direction over a relatively short distance in Earth's atmosphere. One engineer describes it as "any situation where wind velocity varies sharply from point to point."[3] Wind shears can have both horizontal and vertical components. Horizontal wind shear is usually encountered near coastlines and along fronts, while vertical wind shear appears closer to Earth's surface and sometimes at higher levels in the atmosphere, near frontal zones and upper-level air jets.

1. James R. Hansen, *Engineer in Charge: a History of the Langley Aeronautical Laboratory, 1917–1958*, NASA SP-4305 (Washington, DC: GPO, 1987), p. 76.

2. Theodore von Kármán, *Aerodynamics* (New York: Dover Publications, 2004 ed.), pp. 86–91.

3. Terry Zweifel, "Optimal Guidance during a Windshear Encounter," *Scientific Honeyweller* (Jan. 1989), p. 110.

Large-scale weather events, such as weather fronts, often cause wind shear. Weather fronts are boundaries between two masses of air that have different properties, such as density, temperature, or moisture. These fronts cause most significant weather changes. Substantial wind shear is observed when the temperature difference across the front is 9 degrees Fahrenheit (°F) or more and the front is moving at 30 knots or faster. Frontal shear is seen both vertically and horizontally and can occur at any altitude between surface and tropopause, which is the lowest portion of Earth's atmosphere and contains 75 percent of the atmosphere's mass. Those who study the effects of weather on aviation are concerned more with vertical wind shear above warm fronts than behind cold fronts because of the longer duration of warm fronts.[4]

The occurrence of wind shear is a microscale meteorological phenomenon. This means that it usually develops over a distance of less than 1 kilometer, even though it can emerge in the presence of large weather patterns (such as cold fronts and squall lines). Wind shear affects the movement of soundwaves through the atmosphere by bending the wave front, causing sounds to be heard where they normally would not. A much more violent variety of wind shear can appear near and within downbursts and microbursts, which may be caused by thunderstorms or weather fronts, particularly when such phenomena occur near mountains. Vertical shear can form on the lee side of mountains when winds blow over them. If the wind flow is strong enough, turbulent eddies known as "rotors" may form. Such rotors pose dangers to both ascending and descending aircraft.[5]

The microburst phenomenon, discovered and identified in the late 1970s by T. Theodore Fujita of the University of Chicago, involves highly localized, short-lived vertical downdrafts of dense cool air that impact the ground and radiate outward toward all points of the compass at high speed, like a water stream from a kitchen faucet impacting a basin.[6]

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4. Integrated Publishing, "Meteorology: Low-Level Wind Shear," *http://www.tpub.com/weather3/6-15.htm*,accessed July 25, 2009.
5. National Center for Atmospheric Research, "T-REX: Catching the Sierra's Waves and Rotors," *http://www.ucar.edu/communications/quarterly/spring06/trex.jsp*, accessed July 21, 2009.
6. T. Theodore Fujita, "The Downburst, Microburst, and Macroburst," Satellite and Mesometeorology Research Project [SMRP] Research Paper 210, Dept. of Geophysical Sciences, University of Chicago, NTIS Report PB-148880 (1985).

Speed and directional wind shear result at the three-dimensional boundary's leading edge. The strength of the vertical wind shear is directly proportional to the strength of the outflow boundary. Typically, microbursts are smaller than 3 miles across and last fewer than 15 minutes, with rapidly fluctuating wind velocity.[7]

Wind shear is also observed near radiation inversions (also called nocturnal inversions), which form during rapid cooling of Earth's surface at night. Such inversions do not usually extend above the lower few hundred feet in the atmosphere. Favorable conditions for this type of inversion include long nights, clear skies, dry air, little or no wind, and cold or snow-covered surfaces. The difference between the inversion layer and the air above the inversion layer can be up to 90 degrees in direction and 40 knots. It can occur overnight or the following morning. These differences tend to be strongest toward sunrise.[8]

The troposphere is the lowest layer of the atmosphere in which weather changes occur. Within it, intense vertical wind shear can slow or prevent tropical cyclone development. However, it can also coax thunderstorms into longer life cycles, worsening severe weather.[9]

Wind shear particularly endangers aircraft during takeoff and landing, when the aircraft are at low speed and low altitude, and particularly susceptible to loss of control. Microburst wind shear typically occurs during thunderstorms but occasionally arises in the absence of rain

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7. For microbursts and NASA research on them, see the recommended readings at the end of this paper by Roland L. Bowles, Kelvin K. Droegemeier, Fred H. Proctor, Paul A. Robinson, Russell Targ, and Dan D. Vicroy.

8. NASA has undertaken extensive research on wind shear, as evidenced by numerous reports listed in the recommended readings section following this study. For introduction to the subject, see NASA Langley Research Center, "Windshear," *http://oea.larc.nasa.gov/PAIS/Windshear.html,* accessed July 30, 2009; Integrated Publishing, "Meterology: Low-Level Wind Shear," *http://www.tpub.com/weather3/6-15.htm,* accessed July 25, 2009; Amos A. Spady, Jr., Roland L. Bowles, and Herbert Schlickenmaier, eds., *Airborne Wind Shear Detection and Warning Systems, Second Combined Manufacturers and Technological Conference,* two parts, NASA CP-10050 (1990); U.S. National Academy of Sciences, Committee on Low-Altitude Wind Shear and Its Hazard to Aviation, *Low Altitude Wind Shear and Its Hazard to Aviation* (Washington, DC: National Academy Press, 1983); and Dan D. Vicroy, "Influence of Wind Shear on the Aerodynamic Characteristics of Airplanes," NASA TP-2827 (1988).

9. Department of Atmospheric Sciences, University of Illinois-Champaign, "Jet Stream," *http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/cyc/upa/jet.rxml,* accessed July 25, 2009. Lightning aspects of the thunderstorm risk are addressed in an essay by Barrett Tillman and John Tillman in this volume.