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A REVIEW OF 50 YEARS OF AERODYNAMIC RESEARCH WITH NACA/NASA

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Summary

Continuous improvements in flight systems have occurred over the past 50 years due, in part, to continuous improvements in aerodynamic research techniques and capabilities. This paper traces that research from the first-hand perspective of the author who, beginning in 1944, has taken part in the NACA/NASA aerodynamic research effort through studies in low-speed wind tunnels, high-speed subsonic tunnels, transonic tunnels, supersonic, and hypersonic tunnels. New problems were found as systems advanced from low-speed propeller-driven designs to more sophisticated high-speed jet- and rocket-propelled designs. The paper reviews some of these problems and reflects on some of the solutions that have been developed in the course of various aerodynamic research programs in the past. Some of the factors - both technical and non-technical - that have influenced the aerodynamic design, research, and development of various flight systems will be mentioned. Based on the steady progress to date, there is reason to believe that unusual design concepts are likely to continue to appear in the future.

Introduction

Although the first flight of a heavier-than-air powered manned vehicle occurred in the U.S. in 1903, the development and use of native aircraft in the U.S. lagged behind the activity of other nations. One of the concerned people in the U.S. was Charles D. Walcott, secretary of the Smithsonian Institution, who worked hard to sell the idea of a government-funded research organization for aeronautics and succeeded on March 3, 1915, when President Woodrow Wilson signed into law a Navy appropriations bill with a rider establishing the independent National Advisory Committee for Aeronautics (NACA). The sum of $5,000 was included for the committee's first year of operation. The committee was charged "to supervise and direct the scientific study of the problems of flight with a view toward their practical solution" and to "direct and conduct research and experiments in aeronautics." Construction for the NACA began at Langley Field, Virginia, in July 1917. On June 11, 1920, the first wind tunnel was operated and the Langley Memorial Aeronautical Laboratory was dedicated.

Much progress was made in aeronautical research during the first 20 years of the NACA. Some of the accomplishments were the engine supercharger; high-speed airfoil design; basic NACA airfoil research; the NACA cowling; drag cleanup studies; high-lift devices; stressed-skin construction; retractable landing gear; cantilever wings; enclosed cockpit; and so on. These developments were directed toward increased efficiency; increased speed; increased safety and comfort; increased utility and productivity.

The time frame to be reviewed in the current paper begins in the early 1940's. Much of the NACA work at that time was generated by the needs related to World War II. The demands of combat flying resulted in the quest for dramatic changes in performance as reflected in speed, range, altitude, payload capability and agility. The new performance requirements and the introduction of new technologies also introduced new areas of aerodynamic research. Some of these new areas of aerodynamic research will be summarized in the present paper. More detailed discussion of some of these areas of research can be found in references 1 through 6.

Discussion

Problems and Solutions

Speed - When airplanes developed for use in World War II attained higher speeds, the problem of compressible flow appeared. This phenomena occurs when the air velocity over the components of an airplane becomes great enough to compress the air and cause changes in the pressure, density, and temperature of the air. These changes in the property of the air can have an effect on the aerodynamic drag, stability, and control characteristics of an airplane. For example, the changes in pressure distribution due to compressibility caused some airplanes to develop a diving tendency that exceeded the recovery capability of the controls. In other cases, a wing-dropping tendency occurred that was beyond the roll-recovery capability of conventional ailerons. An early fix for the dive recovery was the development of specially designed and located under surface dive flaps. The roll control could be improved by reshaping the profile of the aileron or through the use of spoiler controls. Subsequently, the control power for both pitch and roll was substantially improved through the use of the all-moving and differentially deflected horizontal tail - now a standard control surface on most airplanes.

Propulsion - The propeller became a limiting factor to increased speed since the tip speed of the blade was affected by compressibility. Some effort was expended in the development of high-speed propellers but the gain was quite small. The answer to greater propulsion came with the introduction of rocket and jet propulsion. Such propulsion systems were developed to an operational state in Germany before the end of World War II through the work of von Ohain. Some work had also been done in England by Whittle. Early work on rocket propulsion was done in the U.S. by Goddard. Development of a jet-propelled airplane was underway in the U.S. in the early 1940's with a General Electric engine based on the work of Whittle. The first U.S. jet airplane was the twin-engine Bell P-59 Airacomet which made an initial flight on Qctober 1,1942. The P-59 experienced some problems, one of which was asymmetric thrust from the twin engines. The P-59 was used for training and the design of a single-engine jet fighter was undertaken by Lockheed. Within 143 days the Lockheed P-80 made its first flight on January 9, 1944 and became the first U.S. operational jet fighter.

Airframe Shaping - With greater speed being possible through increased propulsion, a limiting factor became the shaping of the airframe so as to produce minimum drag. Among the shaping techniques that were being investigated by NACA in the 1940's was the use of wing sweep, the use of thinner wing sections, and the use of bodies with higher length-to-diameter ratios. Some of the first tests of swept wings in the U.S. were begun in 1945 in low-speed tunnels at Langley. These tests included swept-back wings, swept-forward wings, diamond-shaped wings, and M-shaped wings. The data thus obtained was to be used in many design studies for years to come. The first U.S. combat airplane with swept wings was the jet-propelled North American F-86 which flew in October 1947. The airplane was originally designed in 1945 with an unswept wing but a design change to the swept wing was made on the basis of the improvement in speed indicated by the post-war studies of swept wings. The first new U.S. fighter to fly following the war was the jet-propelled, straight-winged Republic F-84 in 1946. While the original F-84 was successful, a modification adopting a swept wing was made in 1950 and the performance gains resulted in an extended life for the airplane. The 45-degree swept-wing North American F-100 became the first U.S. supersonic fighter when it flew on May 25, 1953. A delta-wing shape based on a German design was incorporated in the U.S. for the Convair XF-92 airplane. The airplane was successfully flown in 1948 but never became operational. The delta wing design was used later by Convair, in the F-102, F-106, and B-58 airplanes. While these new design shapes were effective in reducing the drag, other aerodynamic problems associated with stability, control, and structures arose.

Test Techniques - Investigation into the transonic and supersonic speed regimes required the development of new test techniques. Some early low-speed studies of swept wings were conducted in the Langley 7- by 10-Foot Atmospheric Wind Tunnel (AWT) which was an improved version of the first NACA wind tunnel. Models in the AWT were mounted to a strut through the tunnel floor which was, in turn, attached to an external balance frame and mechanical scale system. This tunnel was replaced at Langley in the late 1940's by the 300-mph 7- by 10-foot tunnel and the high-speed 7- by 10-foot tunnel. These new tunnels were equipped with a balance frame and mechanical scale system as well as a sting support system using internal strain-gage balances.

Some of the early supersonic studies were made in the Langley 9-Inch Supersonic Tunnel. The models, which were quite small, were generally sting-mounted with the sting being attached to an external measuring system. New and larger supersonic tunnels were placed in operation in the late 1940's and early 1950's. One of the first of these tunnels at Langley was the 4- by 4-foot supersonic pressure tunnel (4'SPT). This tunnel was followed by the Unitary Plan supersonic tunnels at Langley and other NASA research centers at Ames and Lewis. These tunnels provided for continuous-flow tests of large scale models. The models were sting-mounted and incorporated internal strain-gage balances. In addition, these tunnels provided for remote actuation of the angle of attack, angle of sideslip, and angle of roll. The large size models permitted more detailed pressure distribution studies and allowed for remote actuation of control surfaces and for the measurement of control surface loads.

While the tunnels for subsonic and supersonic testing were well advanced by the late 1940's, there were no tunnels capable of testing at transonic speeds since the compressibility effects resulted in reflected tunnel wall shocks that impinged upon the test model and rendered the data invalid. Techniques that were developed to obtain transonic data that was free from reflected shocks included free-fall drop models; free-flight rocket-propelled models; flight wing-flow models and wind tunnel transonic-bump models. In addition, the use of manned rocket propelled experimental airplanes was proposed at NACA-Langley in March 1944. The government decision was to proceed with such a program and this marked the start of the X-series of experimental research airplanes. These methods for transonic testing were soon followed in 1950 by the development at Langley of the first transonic tunnels in which a slotted wall was used to partially eliminate the reflection of shocks from the wall.

Experimental Airplanes - The Bell X-1 airplane broke the sound barrier for the first time on October 14, 1947, when a Mach number of 1.06 was reached. Model tests that proceeded the flight included low-speed tests in the Langley 300-mph 7- by 10-foot tunnel and transonic tests by the wing-flow and transonic-bump methods. The Douglas D-558-II configuration was tested in transonic and supersonic tunnels at Langley and, by 1953, had become the first airplane to fly at twice the speed of sound. The Bell X-2 configuration was tested extensively in the subsonic, transonic, and supersonic tunnels at Langley as well as by the rocket model technique. In 1956, the X-2 achieved a Mach number of 3.2. The North American X-15 was undergoing wind-tunnel tests at NACA Langley in 1956. The airplane was first flown in 1959 and the experimental flight test program was begun in 1960 by the NASA (renamed from NACA in 1958). The X-15 reached a Mach number of 6.7 in 1967 (27 years ago). Prior to that the X-15 had reached an altitude of 354,000 feet, which made the airplane the first vehicle to carry a man to the lower fringes of outer space.

Supersonic Phenomena - The advent of flight at supersonic speeds revealed new aerodynamic problems. These included an increase in longitudinal stability; a decrease in directional stability; the creation of supersonic interference flow fields; and the onset of pitch-yaw-roll dynamic coupling.

The longitudinal stability increase was caused by several factors. One of these factors is the rearward shift of the center-of-pressure for lifting surfaces that results as the shock flow reduces the forward upper surface negative pressure peaks and the lift increases over the aft portion of the airfoil. Another factor contributing to the increase in longitudinal stability with increasing Mach number is the confinement of the wing carry-over lift to the Mach cone flow region over the aft portion of the body. The primary problem associated with the increase in longitudinal stability is the increased control power required for trimming - thus introducing the new problem of excessive drag-due-to-trimming with the attendant concern of decreases in trimmed lift-to-drag ratio for cruising flight. Research directed toward relief for these concerns included the study of wing planform shapes that would minimize the shift in center-of-pressure with Mach number. Other studies were directed toward the use of forward surfaces (canards) to relieve the longitudinal stability and to provide for better longitudinal control.

The directional stability decrease was primarily a result of a decrease in the lift-curve slope of the vertical tail with increasing supersonic Mach number. Contributing factors were the increase in directional instability of the body that resulted from a far-aft center-of-gravity location brought about by the location of jet engines in the afterbody. Research directed toward improving the directional stability characteristics included studies of vertical-tail planforms and vertical-tail location, the use of ventral fins, and the introduction of multiple-tail surfaces. Research was also conducted on the use of forebody strakes which were found to be effective in reducing the unstable body yawing moment.

The creation of supersonic interference flow fields occurs as the supersonic stream flows around an object such as a wing or a body and, as the air stream is deflected by the object, the local air stream is either compressed or expanded. For example, as the air flows around a wing at a positive angle of attack, the flow over the lower surface is compressed and the local dynamic pressure is increased while the flow over the upper surface is expanded and the local dynamic pressure is reduced. These changes in local dynamic pressure can have a significant effect on the aerodynamic behavior of an airframe subjected to the interference flow fields. Research related to the effects of the supersonic interference flow fields was directed toward means of avoiding adverse flow regions and utilizing favorable flow regions.

The onset of pitch-yaw-roll dynamic coupling was a result, primarily, of the geometry of the airframes designed for supersonic speeds. Fuselages became long and slender in an effort to reduce the drag and, with jet engines often mounted in the fuselage, the moment of inertia along the X-axis became much larger than that along the Y-axis and this brought about a divergent coupling motion between pitch and yaw.

Post War Designs - A proliferation of airplane designs, both military and civil, appeared in the 1950's in which application was made of much of the technology that had been developed during World War II. Among the first jet bomber designs in the U.S. was the Boeing B-47. The preliminary design for this bomber began in 1943 with a straight wing arrangement. By 1945 the design was changed to incorporate the newly discovered swept wing. This version of the B-47 first flew in 1947. The B-47 was soon to be followed by the larger strategic bomber, the Boeing B-52 which was also a swept-wing jet that first flew in 1952. The original design for what was to become the B-52 began as a turboprop design that was soon changed to jet propulsion. The first U.S. swept-wing, jet-propelled civil transport - the Boeing 707 - flew in 1954. The 707 was a private venture of the Boeing company that was based, in part, on experience gained with the B-47 and B-52 bombers.

Many supersonic fighter design appeared in the 1950's with a variety of shapes including swept wings, delta wings, and thin straight wings. Some of these airplanes were built and flying when unexpected aerodynamic problems were encountered. The North American F-100, for example, experienced pitch-yaw coupling and low directional stability which lead to several crashes. Additional wind tunnel tests were made that indicated the need for an increase in the vertical tail area of about 27 percent. Several other designs were found to have inadequate directional stability in wind-tunnel tests and modifications were made through changes in the tail geometry and through the introduction of ventral fins. Later designs such as the McDonnell Douglas F-15 made use of twin vertical tails.

An example of the utilization of wind-tunnel data prior to production and flight may be seen in the McDonnell F4H Phantom Navy shipboard fighter. Extensive tests in NACA Langley tunnels in the late 1950's revealed several problems that included poor high-lift stability and a severe pitch-up; inadequate directional stability; and low effective dihedral. Geometric changes to the design to improve these deficiencies included sharply drooping the tail surface, adding outboard wing leading-edge extensions, and turning up the wing tips. The modified airplane flew in 1958 as a Navy shipboard fighter and was adopted by the U.S. Air Force in the early1960's and remained in service for many years.

High drag was a problem for some designs in the 1950's and, in the case of the Convair F-102, prevented the airplane from achieving the required supersonic speed. Tests were made in the Langley 8-Foot Transonic Tunnel in which the newly researched transonic area-rule concept was applied. The airplane was modified and was then able to fulfill the supersonic requirements. Many other designs of the same time period made use of the transonic area-rule to reduce the transonic drag. The technique was later extended to the reduction of drag at supersonic speeds with what was known as the supersonic area rule.

Variable Wing-Sweep - The investigations of sweep-wing designs in the 1940's and 1950's indicated the advantages of sweep insofar as increased speed capability was concerned. There were, however, some problems at low speed that are related, in particular, to the attainment of high lift. The desire to attain the high speed advantages of wing sweep without the disadvantages at low speed lead to extensive research studies of variable wing-sweep concepts. Some early flight research was done beginning in 1951 with the Bell X-5 variable wing-sweep airplane which had, to some extent, been inspired by German research. Wind-tunnel studies of variable-sweep concepts were begun in the late 1950's partly as an outgrowth of a British request for a study of a design by Barnes Wallis for a variable-sweep supersonic transport known as the Swallow. Tests of the Swallow were made at NASA Langley in 1958. These tests gave rise to investigations of many variable-sweep concepts that included multimission fighters and supersonic transports. Operational aircraft that benefited from these investigations include the F-111, the FB-111, the F-14, and the B-1.

The Quest for Supersonic Efficiency - In the early 1950's, a military requirement was proposed for a sustained supersonic cruise strategic bomber that would also have the capability of achieving low-altitude, high-speed, penetration. The requirement lead to an expanded experimental and theoretical research program to aid in the development of such a concept. The principal research concepts investigated were delta wings; highly-swept twisted and cambered wings; canard control arrangements; and outboard tail arrangements. Each type had advantages and disadvantages-typically, configurations having the highest aerodynamic efficiency suffered from problems such as weight, stability, producibilty, and incompatible subsonic and supersonic characteristics. The delta-wing-canard arrangement was selected for the North American B-70 design with the hope that there would be an augmentation of wing lift from the compression field of the body. The advantage was not fully realized but the B-70 became a successful supersonic research airplane.

Very good supersonic aerodynamic efficiency was achieved through the use of highly-swept twisted and cambered wings, but there were problems with weight and with low-speed high-lift aerodynamics. While such a wing design has not been used in an operational airplane, it is the highly-swept arrow wing that is depicted on the NASA logo.

The thrust for supersonic efficiency began as a military requirement but in the late 1950's the

NACA research emphasis was directed toward the development of a supersonic commercial air transport (SCAT). Among the SCAT concepts were those with highly-swept twisted and cambered wings; delta wings; variable wing-sweep; canard controls; outboard-tail controls; aft-tail controls; and three-surface arrangements. While a program to develop a U.S. supersonic transport was canceled in 1971, the research directed toward the development of such an airplane continues to the present time.

Missile Research - The development of missiles was essentially nonexistent in the U.S. until the activity was accelerated in the late 1940's in part by the influx of German missile technology. One of the early U.S. missiles, the Nike Ajax, experienced some unusual flight behavior such as tumbling out of control when maneuvering at high altitudes. The limited amount of wind-tunnel data available for the design had not indicated any such problem. An extension of the test data to higher angles of attack at NACA Langley indicated that the unusual behavior was caused by a nonlinear variation of pitching-moment that occurred as the forebody lift developed and resulted in instability at high angles of attack. Events such as this revealed the need for aerodynamic data and prompted an extensive research program into the field of missile aerodynamics that was to prove quite beneficial in the design of many missile systems.

Computer Aided Design - A revolutionary change in design and analysis methods began in the mid-1950's. These changes came about with the advent of sophisticated electronic computers with which it was now possible to make design changes and verify the effect of the changes rapidly. Modifications to a design could be evaluated in a matter of minutes rather than a matter of days or weeks as had previously been the case. The same computer techniques used in shaping design concepts can be used to control machine tools as an aid in model construction. One of the earliest displays of these techniques was in 1960 when three proposed tactical fighter concepts were designed, constructed and were under test in the Langley 4- by 4- Foot Supersonic Pressure Tunnel within 13 days.

Computer-aided design and analysis methods, properly used in conjunction with good experimental methods, resulted in obtaining useful data in less time and at less expense than previously possible. Essentially all research and development programs now make use of these techniques.

The Space Age - In the mid 1950's, the development of powerful rocket engines led to the possibility of achieving orbital flight. While the U.S. announced intentions to launch a satellite, it was the Soviet Union that first accomplished the feat with Sputnik 1 on October 4, 1957. The first successful launch of a U.S. satellite occurred on January 31, 1958, with the Explorer 1 that was developed by an Army team under von Braun. A consensus began to form that indicated that a national space program was essential. Contenders for managing such a program included the Department of Defense, the Atomic Energy Commission, and the NACA. The concepts all led to the National Aeronautics and Space Act of 1958, which was signed into law on July 29, 1958. The act established a broad charter for civilian aeronautical and space research and absorbed the existing NACA as the nucleus of the new organization. The National Aeronautics and Space Administration (NASA) subsequently came into being on October 1, 1958. Thus, the basic research of the NACA that was related to aeronautics continued as the new role of space related research was assumed. Many space systems have been developed under the NASA, the most prominent manned systems being the Mercury, the Gemini, the Apollo, and the shuttle. The shuttle represents the first combination of a space-oriented vehicle with an airplane. Many hours of research and wind-tunnel studies went into the design of the space shuttle. Some of the basic research generated in support of space activities have included the characteristics of cambered lifting bodies and the characteristics of various arrangements of variable geometry configurations.

A considerable amount of research information has been obtained for the development of vehicles capable of operating at subsonic, supersonic, and hypersonic speeds. This information includes the effects of body shape, the effects of wing planform, the inclusion of low-observable features, and the integrated effects of body-wing-tail and propulsion combinations. Such information is currently being applied in the development of future designs.

Concluding Remarks

In the early 1940's, airplanes were propeller-driven and were limited to top speeds of about 400 mph. During that time period, a considerable amount of wind-tunnel testing as well as flight testing was underway at the National Advisory Committee for Aeronautics (NACA) laboratories with the primary emphasis being on the development of airplanes for use in the World War II effort.

Following World War II, a new era began in aerodynamic research with the introduction of rocket- and jet-propulsion systems and the extension of flight into the supersonic regime. This new era of research required the development of new test facilities and new test techniques.

In the late 1950's, the era of space flight had begun and a new research organization, the National Aeronautics and Space Administration (NASA), was created with the NACA being the nucleus. By the 1960's, civil airplanes reached speeds up to about 700 mph, military airplanes had reached speeds up to about 1700 mph, research airplanes had reached speeds up to about

4000 mph, and space flight was achieved - suborbital and orbital, both manned and unmanned.

In the 1970's and 1980's, the space shuttle first flew and many new airplane designs appeared - some with application of low-observable features. Research continues at the present time in many areas including improved performance, increased efficiency, and better safety features for current airplanes. Research also continues in the development of future airplanes that would be environmentally acceptable, efficient, affordable, and safe for operation at supersonic and hypersonic speeds.

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