

Historical Contributions to Vertical Flight at the NASA Langley Research Center

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ABSTRACT

The NASA Langley Research Center has had a long and distinguished history in powered lift technology development. This research has formed the foundation of knowledge for the powered lift community worldwide. From aerodynamics to structures, aeromechanics, powered lift, acoustics, materials, stability & control, structural dynamics and human factors, Langley has made significant contributions to the advancement of vertical lift technologies. This research has encompassed basic phenomenological studies through subscale laboratory testing, analytical tool development, applied demonstrations and full scale flight-testing. Since the dedication of Langley in 1920, it has contributed to the understanding, design, analysis, and flight test development of experimental and production V/STOL configurations.

This paper will chronicle significant areas of research through the decades from 1920 to 2015 with historical photographs and references.

1915-1935 LAYING THE FOUNDATION OF UNDERSTANDING

After the Wright brothers first flew in 1903, it was a mere 12 years later that the National Advisory Committee for Aeronautics (NACA) was formed in 1915. Langley Memorial Aeronautical Laboratory in Hampton, VA, was dedicated 5 years later in 1920 as the first NACA research laboratory. (Ref. 1) The National Advisory Committee for Aeronautics was formed to “supervise and direct the scientific study of the problems of flight, with a view to their practical solution.” (Ref. 2) NACA’s formation was justified by the need to catch up with European progress in aviation so that the United States military would not be at a disadvantage. As Langley began to assemble the world’s best aeronautical facilities in the late 1920’s, it became a center of aeronautical development. Vertical lift research was present at Langley from the very beginning. NACA Technical Note No. 4 (TN-4) “The Problem Of The Helicopter” was published in 1920, and written by NACA Chief Physicist Edward P. Warner, with an appendix by a former NACA Chairman, W. F. Durand. The paper states “The gravest charge against the helicopter is its lack of means of making a safe descent when the engine has stopped.” It disproved two common misperceptions that the parachute effect of the stopped blades or the blades spinning backwards could create a safe landing. It then provided a mathematical treatment of the principle of autorotation. This principle was later a major feature in Cierva’s autogyro work and, eventually, in satisfactory helicopter behavior following a power failure. Even as a first publication, TN-4 shows some understanding of twist and rotor inflow considerations.

Early rotors

One of the earliest projects in NACA's initial series of wind tunnel tests was the testing in 1922 of several "helicopter propellers" - actually in autorotation only, to simplify testing. Max M. Munk reported the work in NACA TN-221, 1925. Fixed pitch, adjustable pitch, and self-feathering blades (angle controlled by attached surfaces) were tested (Figure 1).



Figure 1. 1922 rotor test blade.

Throughout the 1920’s and 30’s, basic research was done at Langley on aerodynamics, aeromechanics, structures, propulsion and instrumentation that would form much of the world’s foundation of aeronautical knowledge.

Contributions of autogyros

On May 13, 1929, Harold Pitcairn flew his modified Cierva C-8 autogyro in its first American cross-country flight to Langley Field, adjacent to NACA Langley (Figure 2). This flight was made for demonstration and display at NACA's fourth annual Engineering Research Conference.



Figure 2. Pitcairn and modified Cierva autogyro.

In 1931 the NACA purchased a Pitcairn PCA-2 autogyro and began work in earnest on a well-rounded research study of rotating-wing aircraft. Bill McAvoy (NACA test pilot) flew the PCA-2 to Langley on July 15, 1931. Mel Gough, the other NACA research pilot (who trained a nucleus of military pilots a few years later) quickly soloed in the PCA-2 at Langley. In the next 5 years, the logbooks showed a large number of autogyro flights. The first report on the work with the PCA-2 was "Lift and Drag Characteristics and Gliding Performance of an Autogiro as Determined In Flight," NACA Report No. 434, 1932. The determination of lift and drag characteristics in Report 434 was the first authoritative information on rotor behavior and autogyro performance, and it was an initial step into an extensive program of rotor research. Because of the lack of full-scale information on the fundamental aerodynamic characteristics of rotor systems, the autogyro tests were needed to establish a datum to which further work would be referred. NACA's research "Reports" series are formal publications chosen for research of greatest permanent value, while Technical Memoranda were used for documentation of other types of research. Going back to one of the earliest reports in the series, "An Aerodynamic Analysis of the Autogiro Rotor with a Comparison between Calculated and Experimental Results," NACA Report No. 487, 1934, is one that quickly became a classic reference. The analysis is presented as an extension of the previous work by Glauert and Lock. The extension included treatment of linear blade twist, approximations of the influences of the reversed flow region, tip losses, and a method of calculating the drag coefficient. Based on extensive comparison with the experimental data reported for the PCA-2, the basic aerodynamic analysis was concluded to be quantitatively useable, except for blade motion.

This research followed the classically effective pattern of "providing baseline data from a flight article, providing or refining and extending theory, making theory-data comparisons and wind tunnel-flight test comparisons. This process would use a variety of flight tests, wind tunnel and other experimental testing for defining problems and solutions to problems." (Ref. 4) While the complete, practical helicopter would not appear until the mid 30's, (Breguet, Focke & Sikorsky), basic rotor technologies were researched and developed with autogyros. The autogyro rotor information from Langley formed the basic foundation in rotor aerodynamics, rotor aeromechanics, and blade structural dynamics used in the development of the helicopter.

Langley has to invent instrumentation

In the 1920's and 1930's instrumentation was often not commercially available, and Langley had to frequently design and fabricate instrumentation equipment in support of the flight test activities. (Ref 5) The basic recording devices used in flight testing were the trailing-bomb airspeed with flight-path-angle recorder and the hub-mounted camera that rotated with the blades (figure 3).

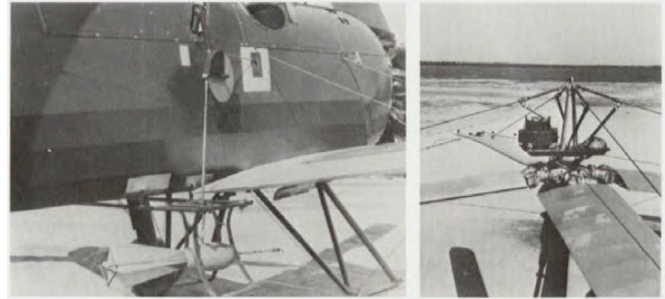


Figure 3. Flight test instrumentation on PCA-2 autogyro.

For very low speeds and vertical descent, the flight path recorder was supplemented by an observer with a sensitive altimeter and battery of stopwatches. The camera was fairly simple to install but the measurement of blade motion by interpreting camera frames was time consuming. The wing pressure measurements used in determining load carried by the wing, required both elaborate installation and tedious measurements of crude instrumentation. In the course of inventing and developing specialized instrumentation, Langley became a national leader in the science of data acquisition and measurement systems and that leadership role continues to the present day.

1935-1945 TRANSITION YEARS FOR ROTORCRAFT RESEARCH

The original justification for forming the NACA was to catch up with European aeronautical technology. During the 1920's, the justification theme evolved into a goal of creating a safe and almost stall-proof aircraft. The autogyro competed with fixed wing aircraft for this safe aircraft goal. In the late 1930's, as World War II approached, research work realigned to be more closely tied to the needs of the Army Air Corps. During World War II, much of the research at NACA Langley shifted to the improvement of military aircraft that were already in production to help the war effort. During this time, the 19-Foot Pressure Tunnel was constructed and would become a workhorse for fixed wing and rotary wing configuration aeroelastic evaluation. Later, this facility had major modifications and became known as the Transonic Dynamics Tunnel (TDT) and is still in operation.

Research transitions from autogyro to helicopter

Blade motion and dynamic test data from a Kellett KD-I Army autogyro was used in the theory-data studies of NACA Report 591 and Report 600, both published in 1937.

Another unpublished paper covered control force and performance measurements, supplemented by NACA pilot assessments of the KD-I. This paper provided recommendations on maneuver limitations and on redesign for better serviceability. The larger YG-2 Autogiro was found by NACA to have such heavy control forces and such violent fluctuations as to make the test article unsuitable for service use. Data were provided to the Army that served as a basis for corrective development work. In April and May 1936, Army Air Corps Pilot Lieutenants Gregory and Nichols received instruction in the flying and maintenance of autogiros at Langley. Thereafter, the military was able to do its own rotating wing acceptance testing, and NACA flight operations personnel were able to return their emphasis to research.

Important external contacts and connections were made in the period of 1935-1940 as a fledgling helicopter community was beginning to organize. Dr. Lewis, NACA Director of Aeronautical Research, served as chairman of the Research Programs session of the pioneering Rotating-Wing Aircraft Meeting at the Franklin Institute, October 1938. Dr. Reid of Langley served as chairman of the Research Programs session at the November 1939 Rotating-Wing Aircraft Meeting at the Franklin Institute. At the 1939 meeting, the entire audience rose to its feet to pay tribute to Igor Sikorsky after his paper on "Commercial and Military Uses of Rotating Wing Aircraft." Mr. Sikorsky was already working toward his successful VS-300 helicopter. His eloquent statements describing his belief in the potential of the helicopter were all the more impressive to the audience considering his reputation as a solid citizen in the fixed-wing aircraft business.

Gradually the aeronautical community began to understand the full potential and utility of helicopters. Therefore, it is not surprising that when NACA was again able to resume a small but intensive attack on the problems of rotary-wing aircraft in the early 1940's, it was the helicopter and not the autogyro that was studied.

During the war years between 1935-1945, the War and Navy Departments relied on Langley for aerodynamic investigations in rotary wing aircraft. While the Air Corps and Army Air Forces did flight testing, Langley was the only organization that conducted fundamental aerodynamic investigations for rotary wing vehicles.

While there was a large effort to support the war effort throughout World War II, basic research continued on a wide range of rotary-wing flight topics: stall patterns on rotor blades; blade loads and bending deflections; control loads; rotor performance; ground resonance; blade dynamics; blade airfoils; and, aeromechanics. As data were gathered, analytical methods were developed and refined. An example of the breadth of the work in this period is provided by the work on rotor airfoils. Numerous wind tunnel tests were run on practical-construction blade specimens, including some corresponding to the rotors tested

in flight and in the Full-Scale Tunnel. Tests of a portion of a blade in yaw were run primarily as an aid to the theoreticians. In response to industry requests, Langley's airfoil specialists designed airfoils specifically for helicopters. Since the helicopter does not have a single, convenient design condition for the airfoil specialist to deal with, the Langley helicopter specialists developed the approach covered in NACA WR L-26, 1944, concluding that low drag airfoil sections must be designed to avoid high drag at high angles-of-attack.

1945-1958 Return To More Foundational Research

A number of rotor flow studies to understand the character of the flow through a rotor were completed during this period. The same group that handled the 30- by 60-Foot Tunnel rotor testing initiated most of the studies. Much of the work was done with models, either in static thrust, in a small-scale model of the 30- by 60-Foot Tunnel, or in the Stability Tunnel.

One of the flow visualization techniques is shown in Figure 4. A similar pattern was later demonstrated with smoke streamers, for a rotor on the helicopter test tower in conjunction with studies of rotor behavior (flapping, torque, thrust) during rapid control application. Single rotor, overlapping (tandem) rotor, and coaxial rotor performance and wake characteristics were explored during this time.

Rotor structural dynamics

While rotor dynamics and loads research was less extensive than for aerodynamics, extremely important basic contributions were made at Langley in the field of rotor dynamic modeling that were the building blocks for approaches today. For example, development of dynamic models with the first large load-lifter provided both a need and an opportunity to demonstrate the value of dynamic models to research problems of ground resonance, blade flutter, and other issues. This model was unique in many respects, including a rotor diameter of 13 feet.

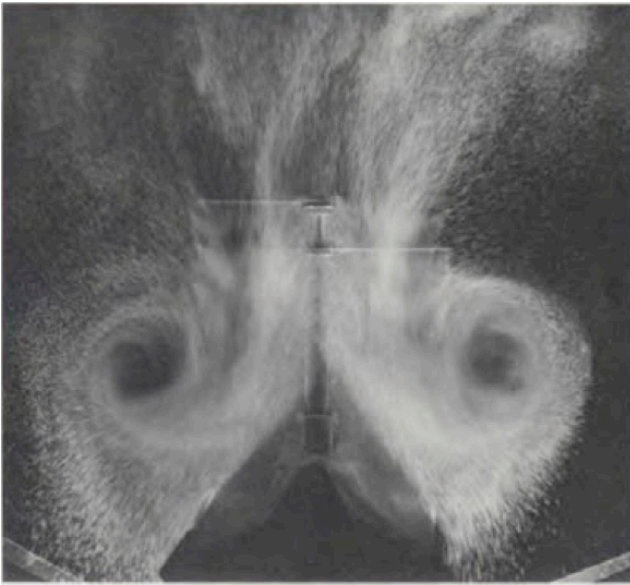


Figure 4. Balsa wood dust flow visualization method for a coaxial rotor. (NACA TN 2220, 1950.)

The model shown in Figure 5 was designed and built at Langley, and it represented a great deal of ingenuity in construction methods for getting the desired stiffness in both blade bending and torsion. Its low cost (approximately \$15,000) was in sharp contrast to the cost of other models of that era. It was designed to provide information applicable to the full-scale article and also to provide general results showing the effects of wide changes in properties such as control stiffness and distribution of weight in the blades. The report, "Description and investigation of a Dynamic Model of the XH-17 Two-Blade Jet-Driven Helicopter," NACA RM L50121, 1951, provides detailed model description and initial results. The titles "A Dynamic-Model Study of the Effect of Added Weights and other Structural Variations on the Blade Bending Strains of an Experimental Two-Blade Jet-Driven Helicopter in Hovering and Forward Flight," NACA TN-3367, 1955, and "The Application of Models to Helicopter Vibration and Flutter Research," Ninth Annual AHS Forum, May 1953, give a good idea of the nature of the follow-on work. A special paper that describes the merits of supplementing the analysis with hardware models is "The Application of Models to Helicopter Vibration and Flutter Research," Ninth Annual AHS Forum, May 1953.

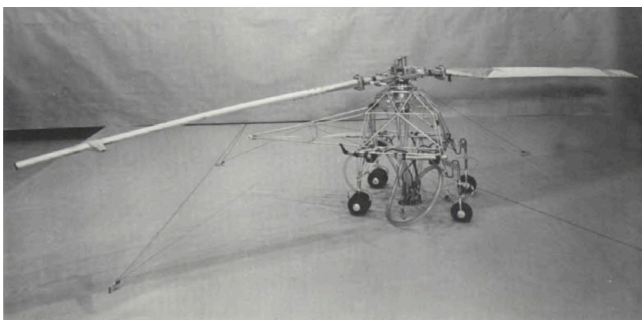


Figure 5. Dynamic model of the XH-17 load-lifter helicopter with a rotor diameter of 13 feet.

In the areas of loads and stresses, a number of efforts were made during this period toward better predictability of vibratory rotor-blade bending loads and stresses. There were also surveys of actual operating conditions such as "Flight Measurements and Analysis of Helicopter Normal Load Factors in Maneuvers" (NACA TN-2990, 1953).

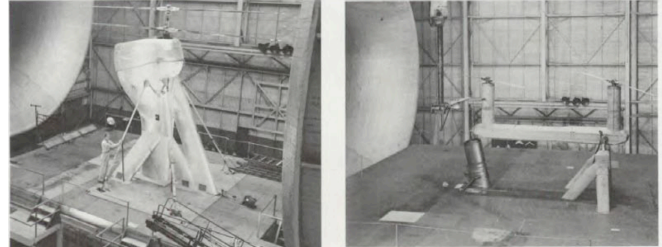


Figure 6. Coaxial and tandem rotor test rigs in 30- by 60-Foot Tunnel.

The emphasis of the rotor tests in the 30- by 60-Foot Tunnel shifted first to basic characteristics of multi-rotor configurations (coaxial and tandem, Figure 6). Later with a single rotor, basic explorations of rotor blade pressure distribution, flow angles, Mach number effects, and extreme-operating condition effects were examined. Much of the multi-rotor work was summarized in "Wind-Tunnel Studies of the Performance of Multirotor Configurations," (NACA TN-3236, 1954) that provided a basis for configuration development.

Stability, control, and flying qualities

Stability, control, and flying qualities became a concern while doing the precision flying required in flight test performance studies. Langley research pilots noted several dominant problems in the handling qualities of helicopters. For example, continuous control action was needed at cruise speeds to prevent the helicopter from diverging to attitudes that would be dangerous. Study of aircraft motion following control movement led to suggested flight test procedures and criteria for examining these problems and assessing attempted improvements. Work of this nature was quickly encouraged by agencies that were beginning to utilize helicopters in greater numbers. For example, the Navy provided an advanced helicopter type for that era, the H03S-1 of Figure 7, specifically for Langley's flying-qualities studies.

Basically, much of this work was essential to determine what helped the pilot quickly sense what the helicopter would do in the few seconds after a control motion or a disturbance. Eventually, a number of helicopter types were sampled to check the generality of the conclusions and uncover additional factors important to effective and safe flying. The criteria thus developed, and the experience behind it, were quickly utilized in basic flying qualities requirements which were general enough to provide a starting point for the more detailed specifications needed for helicopters intended for a specific, defined application. In other words, this Langley work formed the basis for the

development of the MIL standards for helicopter handling qualities. The first such requirements were the flying-qualities portion of the Navy's "SR-189" dated August 1950. With this document as a starting point, and again with heavy reliance on Langley expertise, an updated set of requirements for use with all military helicopters (MIL-H-8501) was created in 1952. When this document was revised beginning about six years later, Langley was the "center of gravity" and meeting place for the revision work.

The tail surfaces of Figure 7 provided demonstration of the ability of a small horizontal area to change the characteristics from rapid divergence in pitch without these surfaces to the ability to fly steadily in rough air without any fore-and-aft control motion. These surfaces were used both fixed and linked to the controls. Tail surfaces are almost universal now, but at that time were not well understood or appreciated for their contribution to stability.



Figure 7. HO3S-1 with Langley developed horizontal tail.

In contributing to stability theory for design use, NACA's view was that there were an ample number of efforts at providing equations of motion of a body moving in three dimensions, and research emphasis was placed on providing a source for the key quantities, such as moment change with angle of attack (TN-2309, 1951) and damping moment due to angular motion. The study of angular-velocity damping (TN-2136, 1950) is still useful, as is the study of tail-rotor effectiveness as affected by the "vortex-ring" range of conditions (TN-3156, 1954).

Helicopter test tower

The helicopter test tower was the only facility constructed by NACA specifically for rotating-wing research (Figure 8). The tower was placed in operation in 1947. It handled rotors up to about 50 feet in diameter, mounted at a height of 40 feet above the ground. The original inspiration for this facility was the ground resonance problem; the shaft was to be free to move at the top, subject to adjustable restraint. However, most of the use of the tower was for other studies. As a shakedown run, the effect of wind speed on rotor power was measured and compared in TN 1698, 1948, with available theory. Miscellaneous efforts included a number of flow surveys and a check of the effect of gusts on blade stresses. The effect on efficiency of high tip speeds was explored well beyond the then-current design values. Later this type of work was extended to include explorations into

rotor-blade stall conditions, and relatively extensive comparisons of blades having different geometry and airfoil sections.

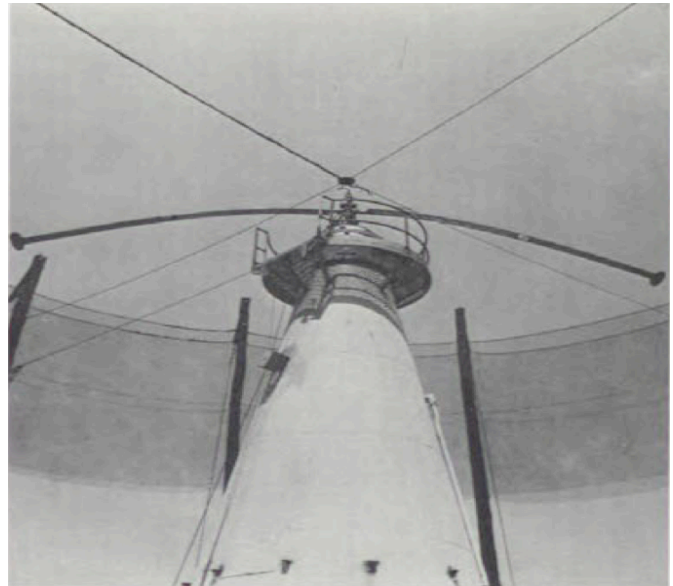


Figure 8. Ram-jet rotor on test tower.

In keeping with Industry interests at that time, considerable work was done on the tower with tip propulsion units. For example, the ramjet rotor shown in Figure 8 was tested both as shown, and with half that rotor radius, to examine the effect of a two-to-one change in centrifugal force on the efficiency with which the fuel spray is burned. Pulse-jets and eventually a pressure jet system were also tested at the helicopter test tower.

1954 Helicopter conference

A high point of the 1950's was the NACA Conference on Helicopters held at Langley in 1954. The 32 papers were divided among sessions on Rotor Aerodynamics, Propulsion, Parasite Drag & Noise, Stability & Control, Loads, Stresses, Vibration and Flutter. Notable Langley authors were Laurence Loftin, Jr., Alfred Gessow, Harry Heyson, F. Gustafson, Robert Tapscott, and Jack Reeder. In attendance were distinguished researchers such as Hugh Dryden, Robert Loewy, Domenic Maglieri, Rene Miller, Alexander Nikolsky, and John Stack.

1958 TO PRESENT - A BALANCE BETWEEN BASIC AND APPLIED RESEARCH

When NACA became NASA in 1958, the agency focus changed to space activities; however, powered-lift aeronautics research remained robust as discussed in technology categories below. A large effort went into a series of aircraft with a tilt-wing layout, like the Boeing Vertol 76 (VZ-2). Langley built and tested a scale VZ-2 free-flight model, which was followed by a full-sized aircraft with a gas turbine propulsion system driving a pair of

oversized propellers (Figure 9). Concurrently, a variety of different configurations were studied through flight test programs and Langley wind tunnel testing (Figures 10 to 12). One result of these activities was a tri-service transport experimental program for the Army, Air Force, and Navy. Known as the XC-142A, a one-ninth-scale model went through remote control flight tests in Langley's Full-Scale Tunnel (NASA TND-2443, 1964) and full-scale flight testing was conducted with Langley test pilots Jack Reeder and Bob Champine (Figure 10). Pioneering research was also accomplished on hingeless rotors with the Lockheed XH-51 design (Figure 13).



Figure 9. Vertol VZ-2 tilt-wing.



Figure 10. LTV XC-142 tilt-wing.

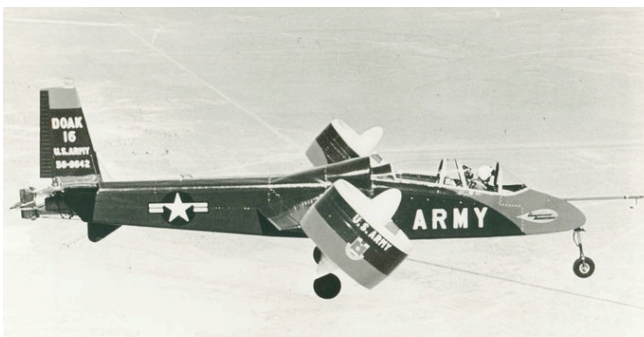


Figure 11. Douglas VZ-4 rotating-ducts.



Figure 12. Canadair CL-84 tilt-wing.



Figure 13. Lockheed XH-51 with hingeless rotor.

In the next several sections, the contributions of Langley to the vertical lift community are described and categorized by discipline area rather than chronologically to provide a clearer picture of the scope of the contributions in these areas.

Structural dynamics

- Ground resonance: The classical ground resonance studies were combined, extended to include damping, and republished in NACA Report 1351, 1958.
- Coupled frequencies: How coupled frequencies occur in tandem helicopters were studied both by means of flight tests using a motor driven shaker in flight and by analytical methods. These studies, initially conducted and published separately, were combined and published in NACA Report 1326, 1957. The helicopter used for these flight tests (Figure 14) was also used for investigation of vibration in critical flight conditions, for determining the effects of moderate blade out-of-track (which proved small), and for a number of flying-qualities investigations. Another investigation of coupled frequencies and mode shapes was made with a unique dynamic model of a single-rotor helicopter.



Figure 14. HUP test helicopter.

- **Blade flutter:** Rotor blade dynamics, including stall flutter, were investigated in the 1960's. The research provided a foundation for industry flutter studies, blade mode shapes and bending frequencies.
- **Equations of motion:** In another basic report, NACA Report 1346, 1958, provided equations of motion for combined blade bending and torsion, with special attention to factors not included in previous analytical treatments.
- **Special configurations:** A summary type report (NASA TN D-737, 1961) reviewed four studies relating to structural dynamics of rotor-powered aircraft, with emphasis on problems of concern for tilt-rotor and tilt-wing aircraft. The 2-degree-of-freedom resonance, or more accurately, mechanical instability and propeller whirl instability, were among the problems discussed. Rotor-pylon-wing instability problems for tiltrotor and tilt-stopped rotor types were explored at Langley in the Transonic Dynamics Tunnel (TDT), along with analytical studies. TDT continued to support tiltrotor research beyond 2005.
- **Blade flapping behavior:** Analytical studies of blade behavior (TND-4195, 1967 and TND-5032, 1969) take a look at extreme operating conditions. These papers bring out the mechanism whereby rotor blades can become unstable in the forward position, at high coning angles and tip-speed ratios. At conditions far short of actual instability, these studies were important in designing for reduced vibration.

Rotor loads and design conditions

- **Blade airloads and bending moments:** Rotor blade airload distribution, as determined with pressure pickups, was investigated. In another approach, vibratory blade bending moments were measured in flight. Moderate atmospheric turbulence was shown to have only small effects, while retreating-blade stall angles-of-attack were shown to have large effects — particularly on the blade torsional moments and hence the vibratory control loads. It was also shown that for hinged blades, static droop-stop pounding can produce vibratory moments as high as those reached in the high speed flight conditions.
- **Design conditions:** With the cooperation of both civil and government agency helicopter operators, a number of

surveys of the operating conditions (as indicated by airspeed, normal acceleration, altitude, and sometimes rotor rpm), that the helicopter is subjected to in actual use, were obtained and published.

Dynamic stability and control

During this period, a different kind of "dynamic" model began to see extensive use at Langley--"Free-Flight, Dynamic-Stability" VTOL models. These were primarily for exploration of gross stability and control characteristics of novel vertical lift concepts that had not yet been flown. Although this coverage did not include helicopters, the work had a profound influence on the course of events in the vertical lift aircraft community (Figures 15 and 16).

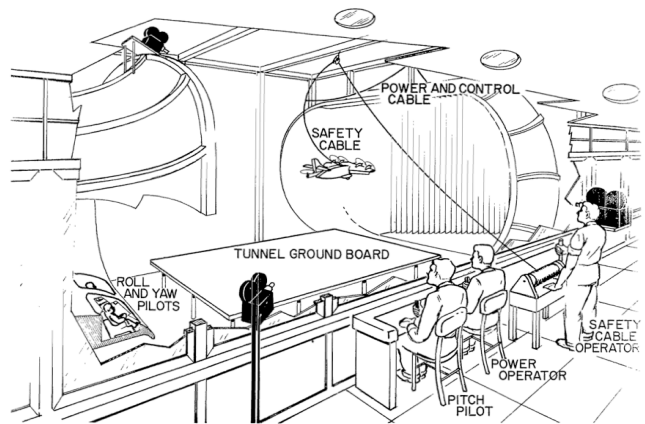


Figure 15. Free-Flight, Dynamic-Stability VTOL model in wind tunnel. (NASA TND-1390, 1962.)

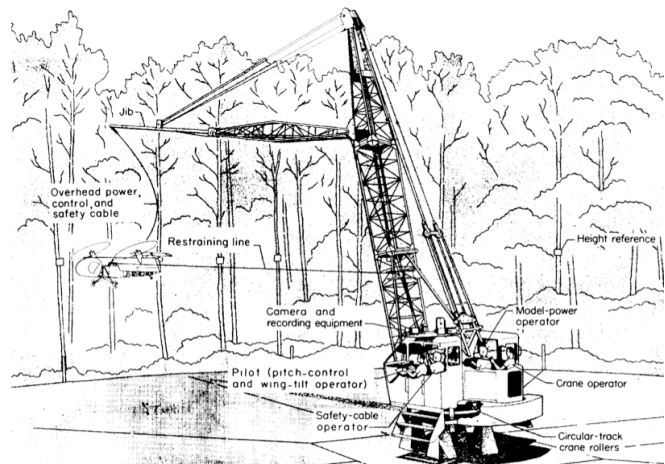


Figure 16. Crane mounted, Free-Flight, control-line facility. (NASA TND-946, 1961.)

Flying-qualities and terminal-area studies

- **Flying qualities:** The importance of damping of angular velocity and of control power (control moments), and their interrelation, was brought out in NASA TND-58, 1959, in a manner that provided the basis for a major portion of formal flying-qualities criteria such as the MIL standards. The heavy emphasis on instrument-flight approaches was a task

for flying-qualities studies, continued in this period. In extending this work, the "in-flight simulator" of Figure 17 was used. Both the simulation system and the handling qualities results have been the subject of numerous published papers, including AGARD report 515 and SAE paper 690693.



Figure 17. Inflight simulator.

A joint U.S. Army/NASA flying qualities investigation was conducted with a single rotor helicopter to determine the effectiveness of tail boom strakes on directional control and tail power during low speed, crosswind conditions. The strakes were employed as a means to separate the airflow over the tail boom and change fuselage yawing moments to improve yaw control margin and reduce tail rotor power. (NASA TP-3278, 1993.)

- **Maneuver studies:** The primary maneuver selected by Langley's pilots to highlight additional flying-qualities problems was the "slalom." It was a series of S-turns taking the helicopter around a series of ground markers, avoiding imaginary vertical extensions of these markers (NASA TND-4574, 1968). It brought out both the best and the worst in helicopters; for example a "tight" (quick and definite) response to controls clearly helped, and over-sensitive collective pitch clearly hurt. Differences between right turns and left turns, not well-recognized before, were suddenly very obvious.
- **Terminal area studies:** Flight investigations were conducted to determine the characteristics and techniques to aid decelerating instrument approaches and instrument departures for VTOL aircraft. The work included special instrument panel displays to the pilot in conjunction with variations in flying qualities and exploration of approach techniques (NASA TND-1489, 1962 and SAE paper 690693). These projects showed the need for reduced pilot workload and better displays to achieve the goal of vertical landing between obstacles with no visibility.

Rotor configurations

- **Hingeless rotor configurations:** Reflection on early experience with "rigid" rotors eventually led NASA to explore the possibilities inherent in removing hinges but providing intentional structural flexibility in the blade. Thus, NASA obtained and flight tested hardware shown in Figure 18, (NASA TND-3676, 1966). NASA and the Army-AVLABS collaborated on a series of hingeless rotor studies involving wind tunnel and flight testing. One of the results

of these model tests was to indicate that some of the problems noted with the flight hardware of Figure 18 might be alleviated by making the blade more flexible in the in-plane direction. To better explore the problems and potential advantages of the hingeless rotor system, the XH-51 helicopter of Figure 13 was purchased by Langley Research Center. While flight testing the XH-51, it was noted that both the H-13 and the XH-51 had a tendency for high in-plane stresses in roll maneuvers and a coupling between lateral and longitudinal control.



Figure 18. Bell H-13 hingeless test helicopter.

- **Compound helicopters at high advance ratio:** Going back to the 1930s, flight work with the PCA-2 winged autogiro and the wind-tunnel "idling" tests of a hingeless rotor also provided some of the background for compound helicopters. A rotor was again tested at high tip-speed ratios in the 1950's, this time in Langley's 300 mph 7- by 10-Foot Tunnel to explore blade flapping limitations. These tests were utilized as one means of checking the extreme-condition theory of TN 3366. During the 1960's, tests in the 30- by 60-Foot Tunnel (TND-2628, 1965) showed several curious effects at tip-speed ratios around 1.0. An interesting, but not necessarily practical result was a relatively high rotor lift-drag ratio. Another result was a reversal in pitch setting variation for trim conditions, which would require specific attention in the design stage.

Impact dynamics, crashworthiness

In 1972, the Langley gantry was converted from the Lunar Landing Research Facility into the Impact Dynamics Research Facility (IDRF). IDRF was used to investigate the crashworthiness of rotorcraft and other aircraft structures. The facility has performed full-scale crash tests of helicopters, light aircraft, system qualification tests of Army helicopters and vertical drop tests of composite fuselage sections. It is currently known as the Landing and Impact Research (LandIR) facility.

- **CH-47 Crash Test Series (1975-1976):** In 1975 and 1976, two full-scale crash tests of the CH-47 "Chinook" helicopter were performed in support of the U.S. Army Aviation Applied Technology Directorate (AATD). Test data were used to: evaluate the performance of load-limiting seats, the structural integrity of cargo restraint systems, the

structural response of the airframe, and validation of KRASH models. These tests also enabled engineers to validate the crash test procedures used at the IDRf facility.

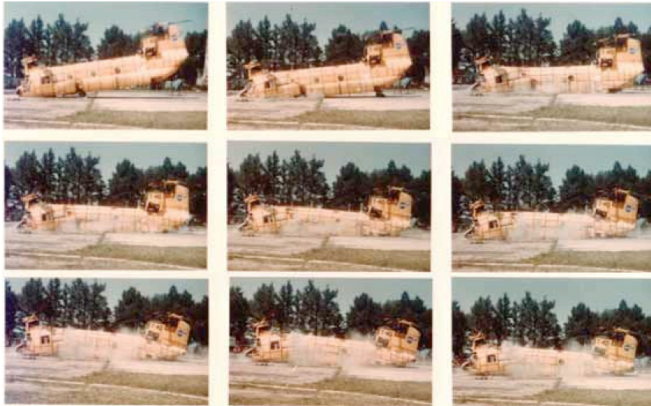


Figure 19. Deformation of CH-47 helicopter during crash testing.

- Wire Strike Protection System (WSPS) Qualification Testing (1979-1987): Qualification testing was conducted at the IDRf to verify the performance of the passive WSPS design on all Army helicopters. Testing was conducted by swinging the helicopter from the gantry into 3/8-in. steel cable that was supported on either side of the gantry by telephone poles. The passive WSPS concept, as validated during tests at the IDRf, has been highly effective in protecting helicopters against mishaps caused by wire strikes. Fewer accidents, injuries, and fatalities have resulted in Army and civilian helicopters that are equipped with WSPS. Currently the passive WSPS systems are installed fleet-wide on all military helicopters and are optional equipment on many commercial helicopters.

- Full-Scale Crash Testing of Composite Material Helicopters (1985, 1987, 1999): Full-scale crash qualification tests were performed at the IDRf on the Bell and Sikorsky Advanced Composite Airframe Program (ACAP) helicopters. These tests demonstrated the successful application of composite materials to save weight and maintenance costs in rotorcraft design, while also achieving improved crash performance. In 1999, a crash test of the Sikorsky ACAP helicopter (flight test article) was performed at the IDRf for the sole purpose of generating test data for validation of a finite element simulation using a state-of-the-art commercial code. This project represented the first attempt to develop a full three-dimensional finite element crash model of a helicopter, to execute a structural impact model of a composite airframe, and to perform test-analysis correlation to validate the simulation. Results provided a successful demonstration of the capabilities of commercial crash simulation codes, thus building confidence in the application of these codes as crashworthy design and qualification tools.

- Testing of Cockpit Air Bag System (CABS) (1993): Two full-scale crash tests of AH-1S Cobra helicopters were conducted at IDRf to demonstrate the performance of active

crew restraint systems under realistic crash conditions (Figure 20). The U.S. Army has ordered retrofit of UH-60 Black Hawk and OH-58 Kiowa Warrior helicopters to be outfitted with CABS based in part on the results of this successful test program.



Figure 20. Crash test of AH-1S helicopter with CABS crew restraint systems.

- Qualification Tests of an External Fuel System (EFS) (1994, 1999): Qualification tests were performed at the IDRf to demonstrate impact performance characteristics of the EFS on UH-1 Huey helicopters (1994) and the UH-60 Black Hawk helicopter (1999). The EFS must meet stringent impact requirements with minimal or no leakage. The EFS on both airframes passed qualification testing enabling extended range and/or increased payload per mission.

- Transport Rotorcraft Airframe Crash Testbed (TRACT) (2013, 2014): In 2013 and 2014, full-scale crash tests were performed at the LandIR of CH-46E fuselages for the purpose of evaluating the crashworthiness of transport-category rotorcraft. Both TRACT tests represented a combined DOD/government/industry collaboration with as many as 18 separate onboard experiments. The first test was conducted with the airframe in a baseline configuration, while the second test was conducted with the airframe retrofitted with three different composite energy absorbing subfloor concepts to evaluate the benefits to occupant safety.

Acoustics

While propeller acoustic testing had gone back to the late 30's (NACA TN-679, 1937), acoustic research would not advance rapidly until computers were applied to processing complex theoretical calculations. (Ref 4) A vibrant acoustic research program has been conducted at Langley since the 1970's. The scope of the research is broad and includes fundamental, theoretical, analytical, experimental, as well as applied research in aeroacoustics. Research emphasis is on the fluid mechanics and acoustics of jets, nacelle and liner aeroacoustics, rotorcraft and propeller/open rotor, noise, atmospheric sound propagation, and acoustic flight testing. Objectives of the research are to understand the noise generation process, to develop methods for predicting acoustics and flow fields and their interactions, and to identify and demonstrate noise reduction and control

techniques. Experimental research is conducted in anechoic facilities, in laboratories, in wind tunnels, and on vehicles in flight. Current code development is based on first principles computational methods in conjunction with the Lighthill acoustic analogy, and a new Aircraft Noise Prediction Program (ANOPP2) is under development to enable the expansion of the empirical and semi-empirical-based ANOPP to include high-fidelity, physics-based tools. Langley researchers have led many acoustic elements of projects that have had impact on design of quieter rotorcraft blades, including the NASA/AHS Noise Reduction program where the phenomenon Blade Vortex Interaction (BVI) was identified. Other acoustics research was conducted under the Short Haul (Civil Tiltrotor) program, the Higher Harmonic Aeroacoustic Rotor (HART I and II), and the DARPA program for Helicopter Quieting, highlighting Langley's lead role in the nation for helicopter noise prediction.

Langley also has a number of unique facilities that are used for rotorcraft acoustic research;

- Quiet Flow Facility (QFF), shown in Figure 21, is an anechoic, open jet facility designed for low turbulence and low structural-borne noise. The chamber is approximately 30 ft by 20 ft by 31.5 ft high and the jet can reach velocities near Mach 0.9 depending on inlet nozzle diameter.
- Mobile Acoustic Flight Test Facility is a collection of hardware that can be deployed to make acoustic measurements of flight test vehicles. The system consists of two trailers for control and data acquisition, dozens of wireless microphone stations that can be configured for specialized testing, a weather measurement system, and portable generators for operation at remote sites.
- 14- by 22-Foot Subsonic Tunnel Open and Closed Jet Test Sections with Acoustic Treatment, shown in Figure 22. The tunnel is an atmospheric, closed-circuit tunnel that was designed to test powered lift models in low subsonic test conditions. The facility can be configured as a closed wall wind tunnel or as an open jet, with a Mach number range from 0 to 0.3.

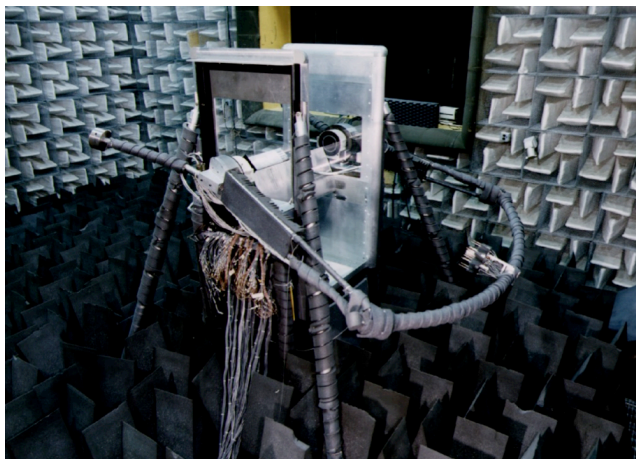


Figure 21. Quiet Flow Facility test section.



Figure 22. 14 by 22-Foot Subsonic Tunnel open jet with acoustic treatment.

Aeroelasticity

The many contributions to aeroelasticity made at Langley, particularly in the Transonic Dynamics Tunnel (TDT), are described through the 2001 timeframe in NASA TM-2001-211054, "A Historical Overview of Aeroelasticity Branch and Transonic Dynamics Tunnel Contributions to Rotorcraft Technology and Development." (Ref 6) The report describes the tests conducted in the facility for helicopters and tiltrotors and the analysis development in aeroelasticity, vibration, structural optimization, and damping. Particularly significant contributions in the area of propeller whirl flutter and increasing the stability boundary for tiltrotors were made at the TDT in the 1990-2000 timeframe. Since 2001, research at the TDT has continued to benefit Government and industry designs for aeroelastic, dynamic, and vibratory loads research.

Aerodynamics

- Airfoils: With the progression and development of computational analyses and the growing capability of computing power, Langley researchers with the Army AVRADCOM explored new airfoil designs for helicopter main rotor and tail rotor blades. Manufacturing techniques had improved to allow more than a single airfoil to be used along the radius of the blade, and airfoils optimized for different working sections of the rotor blade were designed using advanced viscous methods and validated in Langley's wind tunnels. The work done in the late 1970's through the early 1990's developed the RC-X-XX series of airfoils (NASA TP-1396, 1979; NASA TP 1864, 1981; NASA TP 3009, 1990). The RC-series airfoils have been put in service on the Carson Sikorsky S-61, the Bell 206 tail rotor, and are planned for the MD500 main rotor.
- Interactional Aerodynamics: Langley's contributions to the understanding of interactional aerodynamics between the rotor and the fuselage, and later expanding to main rotor/tail rotor and rotor/empennage interactions, began as a program

called the Rotor Body Interference (ROBIN) set of experiments in 1975 in the 14- by 22-Foot Subsonic Tunnel. (See NASA TM-X-3185.) Follow-on experiments using the ROBIN fuselage shape were conducted over the next 20 years. One of the most significant sets of data during that time was rotor inflow data acquired with a new instrument called a Laser Velocimeter (LV). The data were published in a series of reports and formed the basis for computational validation of rotor wake predictions. Widely-used throughout the community at the time, those data are still being referenced in current publications. A summary of the inflow data was published in 2002 in the *Journal of Aircraft* (Vol. 39, No. 5).

- Configuration evaluation: Langley’s capability to conduct experiments on models of approximately 25 to 40-percent scale using advanced measurement techniques in the 14- by 22-Foot Tunnel was invaluable on several occasions to answer time-critical questions for DoD configurations. Particularly, in the late 1990’s, as Comanche was undergoing flight testing, Langley conducted priority testing on the configuration to identify the source of tail buffet. More recently, Langley and the Army conducted configuration testing for a possible upgrade to the Kiowa Warrior, and this test effort was awarded the 2013 AHS Grover Bell Award (see Figure 23.)

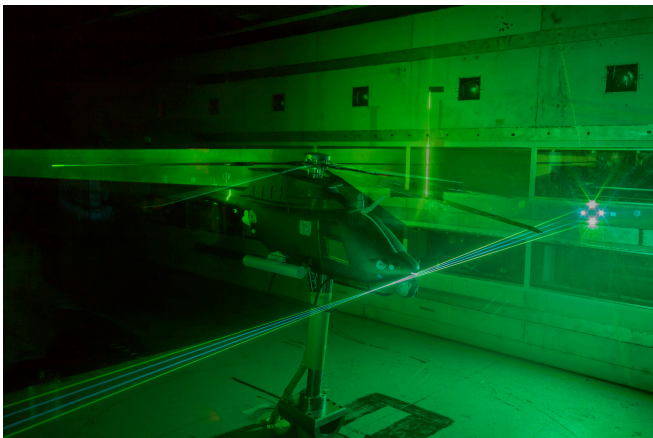


Figure 23. A 37-percent scale powered model of an advanced Kiowa Warrior helicopter is tested in the 14- by 22-Foot Subsonic Tunnel using advanced laser measurement techniques to assess the air flow around the configuration.

- Computational method development: Langley’s capabilities in high-performance computing have been applied to unsteady rotorcraft problems with spectacular results. In particular, the application of the structured-grid, Reynolds Averaged Navier-Stokes (RANS) code OVERFLOW has become a widely-used tool throughout the industry. At Langley, OVERFLOW upgrades and improvements are made by the developer, Pieter Buning, and distributed to the community of users. OVERFLOW has been used by NASA to identify and quantify fuselage/wake interactions and active flow control effects as described in many recent AHS and AIAA papers. NASA Langley has also developed unstructured-grid RANS

capability that has been applied to rotorcraft problems in the computational code FUN3D. In the recent paper “Discrete Adjoint-Based Design for Unsteady Turbulent Flows on Dynamic Overset Unstructured Grids,” (AIAA Journal, Vol. 51, No. 6, pp. 1355-1373, June 2013) Nielsen and Diskin document the capability to apply the adjoint-based computational method to unsteady flows. This development forms the basis to apply formal adjoint optimization methods to rotorcraft configurations, allowing the coupling of aerodynamics, acoustics, structures, and aeroelasticity disciplines. It is anticipated that this breakthrough may form the next giant step for vertical lift design and analysis. Figure 24 shows a sample rotorcraft flowfield calculation with FUN3D.

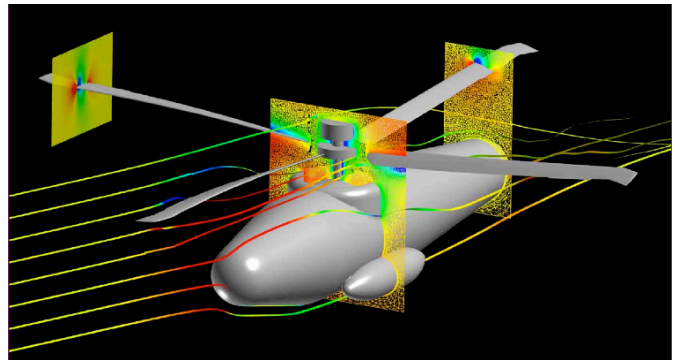


Figure 24. FUN3D simulation of the UH-60 rotor system in the National Full-Scale Aerodynamics Complex.

WORKFORCE AND PARTNERSHIPS

In 1970 Fred Gustafson wrote “NACA/NASA’s most effective past contributions in rotating-wing-aircraft research have involved the providing of an understanding of fundamentals.” He also wrote; “An illustration of the depth and breadth of the helicopter research by the Langley group is that its published work — plus some otherwise unpublished work — forms the primary basis for the book, “Aerodynamics of the Helicopter” by Gessow & Myers, which was originally published in 1952.” Al Gessow worked at Langley from 1944 to 1959. The durability of the book’s content is attested to by its re-publication without revision or extension in 1985.

Beyond the large volume of research into vertical and powered-lift aircraft technology that came from Langley, many people that were employed at Langley went on to work throughout industry, academia and other government agencies over the years. For example, the majority of the key Army-AVLABS personnel in the 1960’s and 1970’s were NACA/NASA Langley “alumni.” They continued the research culture and methods that were trademarks of Langley researchers in other locations.

While Langley had always worked in close partnership with the Army, in 1970 NASA Langley and the Army Air Mobility Research and Development Laboratory (AMRDL) entered into a special master research agreement that

allowed Army research staff to be embedded in the NASA organization at Langley. Army and NASA researchers worked side-by-side on rotorcraft research problems, and many of the highlights related in this paper are a result of the joint work. The agreement has changed over time; however, Langley and the Army Aviation Development Directorate and the Army Vehicle Technology Directorate still maintain a strong partnership at Langley.

CONCLUDING REMARKS

In summary, Langley Research Center has had a long and distinguished history in rotorcraft and powered-lift technology development. This research has formed the foundation of knowledge for the rotorcraft and powered-lift community. The research, reports, and accomplishments cited in this paper are only a small sampling of the total body of work in vertical lift generated over the last century at NASA Langley. In acknowledgment of the significant contributions to vertical lift that Langley Research Center has made since opening in 1920, the site was selected for recognition from the AHS International as a Vertical Flight Heritage Site in 2015.

DATES OF SIGNIFICANCE

| | |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| March 1915 | Initial legislation leading to the formation of National Advisory Committee for Aeronautics, (NACA). |
| 1917 | Construction begins on Langley Memorial Aeronautical Laboratory. |
| June 1920 | Langley Memorial Aeronautical Laboratory dedication. |
| May 1920 | Publication of NACA TN No. 4, The Problem Of The Helicopter. |
| May 1929 | Harold Pitcairn makes first flight of Cierva C-8 autogiro in the US from Philadelphia to Langley Field. |
| 1930 | Full-Scale Tunnel (later renamed the 30- by 60-Foot Tunnel) construction. |
| July 1931 | Bill McAvoy (NACA test pilot) flies PCA-2 Autogiro to Langley. |
| May 1932 | Publication of "Lift and Drag Characteristics and Gliding Performance of an Autogiro as Determined In Flight", NACA Report No. 434. |
| January 1934 | Publication of "An Aerodynamic Analysis of the Autogiro Rotor with a Comparison between Calculated and Experimental Results", NACA Report No. 487. |
| October 1938 | Rotating-Wing Aircraft Meeting at the Franklin Institute, Research Session chaired by Dr. George W. Lewis, named NACA Executive Officer in 1919 and the NACA Director of Aeronautical Research 1924-1947. |
| 1939 | 19-Foot Pressure Tunnel constructed at Langley. (After major modifications, the tunnel reopened in 1960 as the Transonic Dynamics Tunnel.) |
| November 1939 | Rotating-Wing Aircraft Meeting at the Franklin Institute, Research Session chaired by Dr. Henry J. E. Reid, Engineer-In-Charge of NACA/NASA Langley from 1926-1960. |
| 1946 | Construction of Langley helicopter rotor test tower. |
| August 1950 | Flying-qualities portion of the Navy SR-189 specification developed. |
| 1952 | Military helicopter requirements (MIL-H-8501) document. |
| May 1954 | NACA Conference on Helicopters. |
| October 1958 | NACA becomes NASA. |
| October 1959 | Vertol turns VZ-2 over to Langley to conduct Army flight testing. |
| 1960 | Army delivers VZ-4 to Langley for testing. |
| June 1964 | Langley orders an XH-51 for flight testing. |
| May 1966 | XC-142 arrives at Langley for testing. |
| October 1966 | Langley test pilots fly CL-84. |
| 1970 | V/STOL (later modified and renamed 14- by 22- Subsonic) Tunnel constructed at Langley. |
| 1972 | Lunar Landing Research Facility is converted to Impact Dynamics Research Facility (IDRF), later renamed the Landing and Impact Research (LandIR) facility. |
| 1974 | CH-47 crash test series begins. |
| 1975 | Rotor Body Interference (ROBIN) fuselage testing begins at Langley. |
| 1975 | Dr. Feri Farassat, theoretical aeroacoustician at NASA Langley, publishes acoustic theory Formulation 1 for helicopter rotors. |
| 1980 | Dr. Farrasat publishes acoustic theory Formulation 1A. |
| 1982 | Rotorcraft series (RC-X-XX) airfoils designed and tested. |
| 1985 | Full-Scale Tunnel and Lunar Landing Research Facility designated as "National Historic Landmarks." |
| 1985 | ACAP series of crash tests begin at IDRF. |
| 1986 | Rotor inflow measurement testing begins at Langley. |
| 1987 | Tail Boom Strake patented. |
| 1993 | CABS series of crash tests begin at IDRF. |
| 1995 | WRATS Tiltrotor aeroelastic evaluations begin in the TDT. |
| 1995 | Comanche wind tunnel testing begins in 14-by 22-Foot Subsonic Tunnel. |
| 1998 | Short Haul (Civil Tiltrotor) Acoustic Evaluations. |
| 2001 | AIAA Historic Sites Committee selects Langley Memorial Aeronautical Laboratory as an Historic Aerospace Site for noteworthy and significant contributions made in aeronautics and astronautics culture and technology. |
| 2005 | Heavy Lift Slowed Rotor Compound testing in 14- by 22-Foot Subsonic Tunnel (Army RD&A Award, 2007). |
| 2012 | Kiowa Warrior testing in the 14- by 22-Foot Subsonic Tunnel (AHS Grover Bell Award, 2013). |
| 2013 | First adjoint-based optimization method developed for unsteady, dynamic overset unstructured grid computational fluid dynamics analysis of rotorcraft. |
| 2013 | Transport Rotorcraft Airframe Crash Testbed testing begins at LandIR. |

REFERENCES

¹Orders of Magnitude – A History of the NACA and NASA, 1915-1990, NASA SP 4406, 1989.

²Langley Research Center history,
http://crgis.ndc.nasa.gov/historic/Langley_Research_Center

³History of NACA/NASA Rotating-Wing Aircraft Research, 1915-1970, Vertiflite articles, 1970.

⁴A Review of Propeller Noise Prediction Methodology 1919-1994, NASA CR-198156, 1995.

⁵From Biplanes to Apollo – The NASA Langley Historic District, NASA NP-2011-11-429-LaRC.

⁶Yeager, W.T., and Kvaternik, R.G.: “A Historical Overview of Aeroelasticity Branch and Transonic Dynamics Tunnel Contributions to Rotorcraft Technology and Development.” NASA TM-2001-21054. Also Army Research Lab, ARL-TR-2564, August 2001.

RESOURCES

NASA Cultural Resources (CRGIS), (Photos and History Clips)
http://crgis.ndc.nasa.gov/historic/NASA_Cultural_Resources_%28CRGIS%29