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Wake Vortex Research

NASA conducted a series of research flights beginning in late 1969 and continuing into the 1970s that studied the dynamics, characteristics, and hazards of wingtip vortices. Data accumulated by the vortex studies contributed to a broader understanding of these dangerous wakes of turbulent air that trail behind every aircraft, and helped the Federal Aviation Administration (FAA) establish safe separation distances between various sizes of aircraft during takeoff and landing operations, and also during cruise flight.

Vortices produced by small aircraft are almost negligible, but vortices created by larger and heavier aircraft can be extremely dangerous for a distance of many miles to a trailing aircraft. Wake vortex and turbulence generated by large aircraft can cause instability, uncontrollable rolls, and sudden loss of altitude. There have been incidents, especially at lower altitudes during landing approaches, when wake turbulence has resulted in fatal accidents because of insufficient time and altitude for pilots to regain full control of their aircraft after being buffeted violently by the powerful vortices.

The first series of NASA wake turbulence research flights were conducted by the NASA Dryden Flight Research Center in 1969-70, when large wide-bodied jet transports were being introduced into commercial and military service and a mix of large, medium, and small aircraft was being seen at nearly every major airport. These first tests measured the strength of vortices created by large "jumbo" aircraft and measured their effects on smaller trailing aircraft. Between the years 1972 and 1974, three additional series of wake turbulence tests were flown at NASA Dryden with emphasis on the use of wing flaps, speed brakes, and spoilers to alter the formation, strength, and behavior of vortices generated by large aircraft.

Smoke streams from on-board generators of a 747 jumbo jet to present a visual picture of the magnitude of wake vortices created by large aircraft. This 747 is the same one acquired by NASA and later modified to carry space shuttles.

NASA Photo ECN-4242

Data from the research flights aided the FAA in establishing the current separation distances that require that during landings a small aircraft must remain six miles behind a large wide-bodied aircraft, and two large wide-body jets cannot be closer than four miles. During takeoffs, three-minute intervals are required between small and large aircraft. Separation distances of up to five miles are also applied between various sizes of aircraft while cruising at or near the same altitude.

Conducting and coordinating the vortex research flights was the NASA Dryden Flight Research Center. Also taking part in one or more phases of the program were the Federal Aviation Administration, the Air Force Flight Test Center at Edwards AFB, the NASA Ames Research Center, the NASA Langley Research Center, McDonnell Douglas, and Lockheed.

What is Wake Vortex?

Every aircraft generates a wake of turbulent air when it flies. This disturbance is caused by a pair of tornado-like counter-rotating vortices that trail from the tips of the wings. The existence of these cylindrical vortices was proclaimed in 1907, just four years after the first powered aircraft flights by the Wright Brothers, following airflow studies by British aerodynamicist F. W. Lanchester.

Aerodynamic lift, which causes an aircraft to rise into the air, is generated by the difference in air pressure as it moves across the upper and lower wing surfaces. As a wing moves through the air, low pressure is created across the curved upper wing surface and high pressure exists under the wing where the surface is fairly flat. This pressure differential creates lift, but it also causes the airflow behind the wing to roll into a swirling mass and form into two counter-rotating circular vortices downstream of the wing tips.

Studies have shown that an aircraft's weight, speed, and shape governs the strength of the vortices and weight is the dominant factor. Small general aviation aircraft like those in the Cessna and Piper general aviation fleets create vortices that are almost undetectable by a trailing aircraft of similar size. Large jetliners, however, leave vortices that can exceed 150 mph in rotational velocity and are still detectable at distances of 20 miles. The strongest -- and most dangerous vortices -- are generated by aircraft that are heavy, are in a clean gear and flaps-up condition, and are flying at slow speeds like those of landing approaches.

Wake vortices can cause violent rolling motions and even flip a small aircraft upside down when a pilot trailing a large aircraft flies into the vortices. The power of these dangerous spinning vortices can cause an aircraft to become uncontrollable. In these instances, crewmembers and passengers have sustained injuries during the periods of buffeting, instability and altitude loss. In most all cases, control of the aircraft is restored if there is sufficient altitude. Some aircraft have sustained serious structural damage when encountering wake vortices but were landed safely. There are, however, cases in which smaller trailing aircraft, during a climb-out after takeoff or during a landing approach, have crashed after entering wake vortices because they were too close to the ground for the pilots to recover full control.

In the early days of flight, this disturbance of air was called "prop wash." Although the vortices were recognized as turbulence, they were not completely understood by most people in the aviation community. Wake vortex also did not present a serious problem to trailing aircraft until large, heavy aircraft like the 747s, DC-10s, L-1011s, and C-5s began flying in the late 1960s and early 70s.

The flying community had been aware of wake turbulence generated by smaller aircraft for years and accepted it as a factor of flying when the first 707-size jet transports began operating in 1959. Larger and stronger vortices created by the new jets then, however, did raise concerns about traffic spacing and a separation distance of three miles was established during landings when pilots were flying on instrument flight rules (IFR). When flying under visual flight rules (VFR), pilots assumed the responsibility of maintaining their own separation distances, and their general knowledge of wake vortex at that time usually resulted in safe operational procedures.

It was the introduction in 1970 of the larger wide-bodied "jumbo" jets with much stronger vortices that led to an effort by the FAA, NASA, the Air Force, and the commercial aviation community to study the growing wake vortex phenomena and establish safe operational distances between similar and dissimilar size aircraft.

The Behavior of Vortices

Since wake vortices are a by-product of aerodynamic lift, they are generated as soon as an aircraft begins to leave the ground. When viewed from in front of an aircraft, or from behind, the circulation of vortices is outward, upward, and around the wing tip.

NASA research has shown that as large aircraft move through the air, trailing vortices tend to remain spaced less than a wingspan apart while sinking at a rate of several hundred feet per minute. Over time, the sink rate will slow and their strength will taper off. Research has shown, however, that vortices can also rise during conditions of ambient thermal lifting.

Vortices of large aircraft often move laterally at speeds of 2-3 knots when they sink to within 100-200 feet of the ground.

In calm wind conditions, vortices created by large aircraft during landing operations can remain for many minutes over the normal touchdown area. They can also slowly drift from one runway to a nearby parallel or crossing runway.

The Research Flights

The first series of wake turbulence research flights by NASA Dryden began in late 1969 and continued into 1970. Three additional series of flights were conducted between 1972-74 with emphasis on the use of wing flaps, speed brakes, and spoilers to alter the formation, strength, and behavior of vortices.

The research flights used large aircraft to generate the vortices and smaller ones to probe them. Each probe aircraft was instrumented to record a variety of parameters, including longitudinal and transverse acceleration, velocity in pitch, roll, and yaw conditions, bank angles, control wheel position, and in some cases angles of attack and sideslip. Ground-based radar was used to measure and maintain exact lateral and vertical separation between the probe and wake-generating aircraft.

A 100-mile long racetrack course over the Mojave Desert was used for the first two series of flights. The other two series of flights were conducted within restricted airspace over and near Edwards AFB, and within the Pacific missile test range west of Vandenberg AFB, Calif.

In the first test series, a C-5A military transport and a B-52 bomber were flown to generate the vortices, while the probe aircraft were a CV-990 four-engine jetliner and an F-104 Starfighter. At a test altitude of 12,500 feet, the CV-990 and the F-104 probed the vortex wakes of both large aircraft at separation distances that ranged from 1 to 15 miles. The wake-generating aircraft were flown in both the clean configuration and with flaps lowered to represent landing configurations.

Also flown, as vortex generators in the first series of flights, were the CV-990, C-5A, and a DC-9 commercial transport. The DC-9 and the CV-990 were also used to probe vortices of the larger aircraft, along with a Learjet 23 business-type aircraft and a twin-engine Cessna 210 general aviation aircraft. The test altitude for all the probes of the second series was 12,500 feet, except for the Cessna flights, which dropped to 9,500 feet. Airspeeds for this series of tests ranged from 130 to 200 knots and separation distances again ranged from 1 to 15 miles. The wake-generating aircraft were flown in both clean and landing flap configurations. The Learjet and the Cessna 210, however, were not flown into the wake of the C-5A while it was in the clean configuration because of flight safety.

On several of the flights, the CV-990 and the C-5A were paired up and flown in formation on a parallel course while probe aircraft flew into the wake vortices alternately to gather comparative data. The CV-990 was then teamed with the C-5A and the same scenario was repeated.

Most of the vortex probes lasted from two to three minutes while the probe aircraft at various speeds, weights, and configurations was accumulating data. When an upset or extreme roll rate was generated by the wake, the probe pilots returned the aircraft to the wake path as soon as possible.

During the second series of tests, conducted in November 1972, the focus was on wide-bodied tri-jets such as the DC-10 and L-1011 series of transports.

The wake-generating aircraft in the second series of tests were a C-5A and a DC-10-40, with a DC-10-10 and a Learjet used to probe the C-5A's wake and an L-1011 and a DC-9 probing the DC-10-40 wake.

The flights revealed that the strength of the vortices produced by the largest and heaviest of the tri-jets, the DC-10-40, was comparable to vortices generated by the C-5A.

The third round of flights was in 1973, when a 727-200 three-engine jetliner was the wake generating aircraft and a PA-30, a Learjet, and an F-104 was the probing aircraft. The effort of this round of tests was to study changes occurring in vortex characteristics during the steeper descent path used in a two-stage noise abatement landing approach. Smoke generators were attached to the wing tips of the 727-200 to help chart differences between vortex flows created during normal landing approaches and the noise abatement approaches.

The fourth and final main series of flights, carried out in 1974, used a 747 jumbo jet as the generator aircraft and a T-37B and a Learjet probed the wakes. The 747 was the same one acquired by NASA that was later modified to carry the space shuttles. The main effort was the investigation of the 747's wake vortex strength while flying with different inboard and outboard flap settings. Earlier NASA wind and water tunnel studies indicated that the strength could be reduced if the plane was flown with greater inboard and less outboard flap deflections.

The tests, conducted over a span of 17 flights, showed that vortex strength was softened with the 30/1 setting -- outboard flaps at 1degree while maintaining a 30-degree deflection on the inboard flaps.

Combinations of inboard-outboard flap settings tested were 30/30, 30/20, 30/10, 30/5, 30/1, and 5/30.

A Learjet and an Air Force T-37 meet in the skies over NASA Dryden for a series of flights to study the hazards of wake vortex generated by large aircraft. Studies conducted from the late 1960s to 1974 used large aircraft as wake generators and smaller instrumented aircraft such as the Learjet and T-37 were flown into the vortices to determine vortex strength and safe separation distances. The 747 is the same one acquired by NASA and later modified to carry space shuttles.

NASA Photo ECN-4243

Pilots flying probe aircraft concluded that the 30/1 inboard-outboard setting provided the best vortex alleviation and the safe-separation distance at that setting dropped from 7.5 miles to 3 miles with the landing gear retracted. With landing gear down, however, the separation distance had to be increased to six miles, a factor that made the configuration impractical.

The study also investigated the use of speed brakes and spoilers to alter the behavior of vortices. Spoilers did reduce the strength of vortices, but the difference was not significant enough to prove suitable.

Tests with the 747 included a look at engine thrust rates as a means of reducing vortex strength, including alternating symmetrical maximum and idle thrust in the inboard and outboard engine pairs. No concrete conclusions resulted but pilots believe that outboard thrust lessened vortex strength more than inboard thrust.

In each of the series of test flights, probe pilots flying near and into vortices experienced varying degrees of instability, altitude loss, and rolling excursions due to strong turbulence. Fortunately, none of the aircraft involved in any of the tests was structurally damaged. Experiences logged by probe pilots included sudden altitude losses of up to 4000 feet, sudden rolls of up to 720 degrees at rates of more than 200 degrees second, and violent yaw accelerations.

In 1979, a brief series of flights with an L-1011 was conducted to determine if the use of spoilers, which had slightly reduced vortex strength on the 747, could be applied on other wide-body aircraft. Flight results, however, showed that although spoilers contributed to some reduction on the L-1011, they were not as effective as with the 747.

The Benefits of Vortex Research

Data produced by the series of vortex research flights aided the FAA in determining safe, minimum separations distances between aircraft to minimize potential hazards that can occur when large and small aircraft are mixed during normal airport operations.

The research data accumulated in the vortex studies also represents a wealth of information that continues to contribute to a broader industry understanding of the turbulent air that trails behind every aircraft.

Into The Future

NASA researchers still continue to learn more about wake vortex and strive to predict and reduce the hazards associated with wake turbulence.

The latest system to be studied is the use of calibrated microphone arrays and laser radars on and near airports to locate and record wake vortices. The thrust of the study is to find out if an acoustic-based wake vortex sensor is feasible for an airport environment. An operational system of this type may be able to give pilots advance warnings of the location and strength of wake turbulence.