Flight Test Studies of the Formation and Dissipation of Trailing Vortices

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A flight test program has been conducted to measure experimentally parameters which describe the characteristics of vortex behavior and their instability. Three basic atmospheric flight conditions were investigated: steady level flight in calm air, steady level flight in light gusting air and light winds, and unsteady flight produced by control surface oscillations in calm air. A DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane were used in the investigation. Smoke grenades were located near the wing tips of each airplane such that the vortices could be seeded with smoke and thus made visible. This made it possible to photograph the vortices and make measurements from the photographs obtained. The experimental results show wavelengths of vortex instabilities, dissipation time of trailing vortices, effects of atmospheric current or gust, and the effect of control surface oscillation. These results provide additional experimental verification of the existence of vortex wake instability predicted by theory and show that small oscillations in pitch at a critical frequency accelerate the dissipation of high-intensity vortices.

Introduction

THE high-velocity flow in trailing vortices behind heavy aircraft poses two potential hazards to lighter aircraft which follow or cross in the path of the heavier aircraft: loss of control and structural failures. The greater weight of current large airplanes together with the recent rise in aircraft traffic density increases the probability of the lighter aircraft encountering these hazardous conditions. One way of minimizing the possibility of exposure to these trailing vortices is to provide sufficient spacing between aircraft. This approach is currently being used by the FAA. However, an improved technique for accelerating the dispersion or decay of vortex wakes is needed for future high-density air traffic patterns. One of the difficulties in finding this type of solution is the lack of theoretical understanding and experimental verification of vortex behavior and its instabilities.

Theoretical treatment of this problem by Crow[1] indicates that trailing vortices do not decay, but undergo a nearly sinusoidal instability which results in the dissipation of the vortices through the formation of a train of vortex rings. Preliminary flight tests were conducted at the Texas A&M Flight Mechanics Laboratory with two aircraft to verify by visual observations the existence of this instability in actual flight. These initial flight tests indicated that the instability of the type predicted by Crow did in fact occur, and that small external disturbances from the surrounding atmosphere had large effects upon the vortex dissipation. These tests also indicated that the airplane control surface could be used to excite vortex instability.

A second phase of flight testing was then conducted to photographically document vortex characteristics and to obtain measurements of parameters which describe the characteristics of the vortex behavior and instability. This paper presents the results of the second phase of flight testing. Results include measurements of the wavelength of the vortex instabilities, dissipation time of trailing vortices, effects of atmospheric current or gust, and the effects of control surface oscillations.

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Flight Test Program

Test Airplanes

Two airplanes were used in the investigation, a DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B. The gross weight of the DHC-2 airplane is approximately 4100 lb, and the gross weight of the T-34B is approximately 2800 lb. The wing loading and span loading of the DHC-2 are 16.4 lb/ft^2 and 1.78 lb/ft^2, respectively. The wing loading and span loading of the T34-B airplane are 15.8 lb/ft^2 and 2.60 lb/ft^2, respectively.

The DHC-2 airplane has instrumentation for wake turbulence research which includes: 1) Angle-of-attack sensors mounted forward of the wing's leading edge at four locations along the span of the wing. Range: $+20°$–$-10°$. 2) Three-axis accelerometers mounted at the airplane's c.g. Range: $\pm 3g$. 3) Three-axis rate gyros mounted at the airplane's c.g. Range: roll, $\pm 40°$/sec; pitch, $\pm 15°$/sec; yaw, $\pm 15°$/sec. 4) Aileron, flap, and elevator deflection angle sensors. Output from the above instrumentation is monitored and recorded onboard the airplane.

Measurements

Photographic methods were used for recording the characteristics of the trailing vortices and the resulting vortex formations. The vortex cores were seeded using smoke from grenades located near the tips of the wings of each aircraft. Photographs of the smoke trailing from the wing tip of each aircraft are shown in Fig. 1.

Most motion pictures were taken through a wire grid mounted 10 ft above the camera at ground level. The frame speed of the camera and a clock mounted in the field of view were used to measure elapsed time. Figure 2 shows a sketch of the grid and camera location.

The grid provided a reference coordinate system from which airplane altitude and distances parallel to the ground plane could be measured. The altitude indicator in the airplane was used to check calculated values of altitude and the airplane's wingspan was used to check measurements of distances.

Both motion picture and still photographs were taken from ground level and from a chase airplane at altitude. Elapsed time for still photographs taken at ground level was recorded manually for each frame taken.

Test Procedure

Flight tests were conducted in straight and level flight, at speeds of approximately 70, 80, 90, and 110 knots and an altitude of approximately 1000 ft. Tests were conducted during both early morning calm air and light turbulent conditions for comparison. Some tests were also conducted in crosswinds of 5–10 mph. Tests of control surface oscillations were conducted during early morning calm air when possible; however, in all cases a steady-state reference test was conducted before and after each series of tests.

Results and Discussion

Three basic atmospheric and flight conditions were investigated: steady level flight in near calm air, steady level flight in light gusting air and light winds, and unsteady flight produced by control surface oscillations in calm air. The difficulty of obtaining photographs adequate for reproduction also imposed additional constraints on the atmospheric conditions. It was found that sun glare from the smoke particles in and around the vortex core revealed more details of the vortex characteristics than the color of the smoke. Thus, on bright, sunny days, only small amounts of smoke were required to seed the vortex core and characteristics of the vortex dissipation could be recorded for longer lengths of time. In addition, photographs taken from the ground upward required a cloudless sky in the background and bright sunlight with a sun position near the horizon. To obtain maximum detail in the air-to-air photographs the chase airplane was flown such that the camera faced toward the sun but at a small angle from the sun to avoid lens flare. This procedure produces glare from the smoke particles themselves, thus giving photographs of greater detail.

Calm Conditions

Flight test results showed that two basic types of vortex breakups occurred in calm air conditions. For extremely calm conditions both types of breakups occurred along the length of a given vortex wake. With increasing time, generally from 1 to 2 min, one type of vortex breakup appeared as simple breaks, as shown by the photographs in Fig. 3A. At other positions along the trailing vortices, a wave formation similar in appearance to that described by Crow[1] was formed. This wave form grew with increasing time until the two trailing vortices touched at the center, as shown by the photographs in Fig. 3B. When contact was made between the two vortices, vortex rings were formed. In general, these vortex rings appeared stable, and lingered for an additional 10–20 sec before dissipating. It was noted that more vortex rings were formed and less simple breakups occurred during tests conducted in later morning hours than during the early hours. At this time of day heat from the sun was probably producing small amounts of turbulence which were undetected by the aircraft's instrumentation.

Two types of simple breakups occurred. One type, as shown in Fig. 4A, appears as a bursting of the core with a resulting turbulent type of dispersion into the surrounding atmosphere. The second type, shown in Fig. 4B, appears as a simple stretching of the vortex core until it dissipates into the surrounding air.

On several occasions, early morning fog or haze prevented photographic documentation of the vortex characteristics; however, visual observations of the trailing vortices showed that this type of atmospheric condition has a significant effect on the vortex dissipation. The vortices broke up very rapidly in the form of simple breaks. For most clear, calm air conditions, the vortex lingered from 1 to 2 min, whereas in early morning haze or fog the vorti-

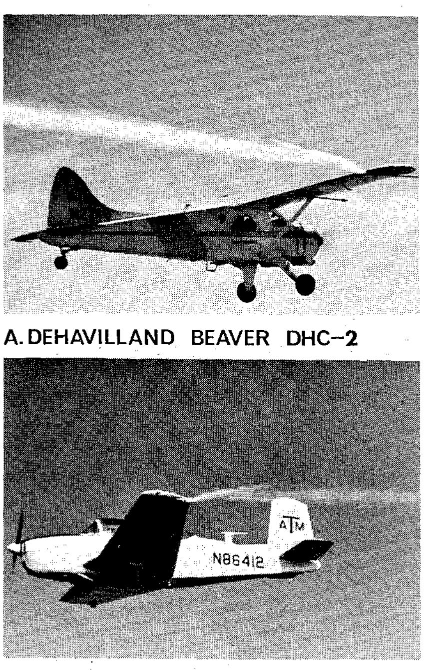


Fig. 1 Smoke seeding of vortex core near the wing tip.

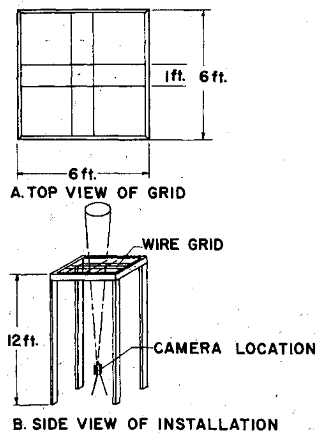


Fig. 2 Sketch of camera and grid installation used for photographing vortices.

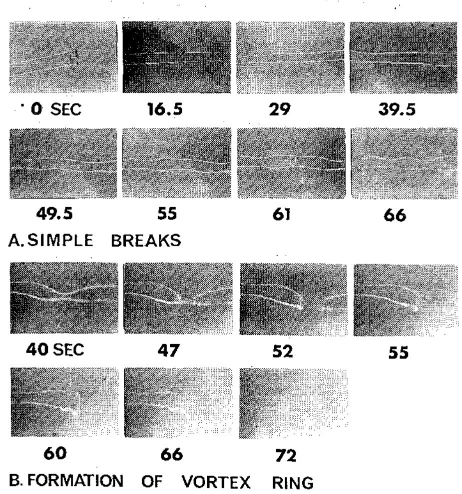


Fig. 3 Photographs of trailing vortex cores showing basic types of dissipations in calm air.

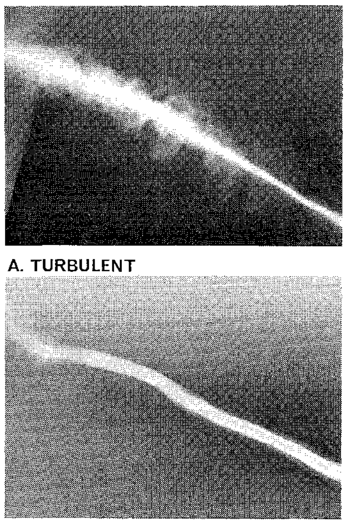


Fig. 4 Photographs of vortex core dissipation in calm air.

ces broke up and dissipated in less than 20 sec. These results indicate that moisture, or high humidity levels, greatly minimizes the exposure time to wake turbulence.

Gusts and Crosswinds

With small increases in atmospheric turbulence, it was observed that sinusoidal wave formations occurred more quickly, more vortex rings were formed, and, in general, the total dissipation time was reduced. Additional increases in atmospheric turbulence, such as that produced by thermal activity in calm winds, resulted in vortex breakup and dissipation before ring formation occurred. The effect of crosswinds was similar to that of gusts. Although wave formations started to form, random breakups and resulting dissipation occurred before the formation of vortex rings.

For all flight tests in which trailing vortices were disturbed by the surrounding atmosphere, sinusoidal-type wave formations occurred. Measurements of wavelengths obtained from motion picture photographs taken through the wire grid are presented in Fig. 5. For a given vortex formation several wavelengths were measured and an average taken. The scatter about this average is also shown in Fig. 5.

The results presented in Fig. 5 show that the wavelength is primarily dependent upon the span of the generating aircraft. These results show reasonable agreement with the constant value predicted in Ref. 1. The large amount of scatter associated with the measurements of

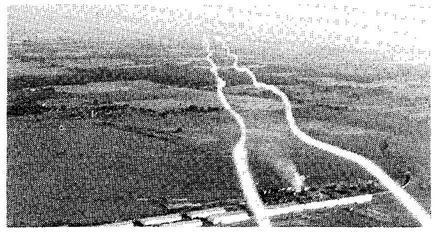


Fig. 6 Vortex instability during near-calm condition.

wavelength could have resulted from several sources of errors. The loss of altitude of the vortex formation with time probably contributed the largest source of error. Observations from the chase aircraft indicated a loss in altitude of approximately 200 ft within a 2 min period of time. These observations also indicated that the loss in altitude was rapid initially and followed by a much slower rate of descent.

Furthermore, although the wave formations shown in Fig. 3B appear to lie in a horizontal plane, observations from the chase airplane indicate that each trailing vortex actually lies in a plane at an angle to the horizontal plane as shown in Fig. 6. An accurate measurement of this angle has not been made; however, the angle appears to closely agree with the theoretically predicted value of 48° in Ref. 1.

Control Surface Oscillations

From the results presented in Fig. 5, it was concluded that a disturbance produced by the aircraft at a frequency corresponding to the wavelength of the vortex instability and the airspeed of the airplane could possibly excite the instability and reduce the vortex intensity. Preliminary results of flight tests made during calm conditions while oscillating the airplane's elevator at these calculated frequencies showed a marked decrease in vortex dissipation time. Results of oscillating the airplane's rudder and ailerons did not produce an appreciable change in the total vortex dissipation time. Thus, additional testing was conducted to define the frequency range and the magnitude of the airplane's oscillations in pitch required to excite the vortex instability and reduce the vortex dissipation time.

Flight tests were conducted using the DHC-2 airplane at an airspeed of approximately 80 knots. The airplane's elevator was oscillated to produce an angle-of-attack change of ±2° at frequencies of ½, ¼, and ⅛ Hz and ±4° at ¼ Hz. Limited tests were conducted using the T34-B airplane to show that similar instability characteristics could be obtained with both aircraft.

Figure 7 shows the results obtained for an angle of attack change of ±2° at the calculated frequency of ¼ Hz.

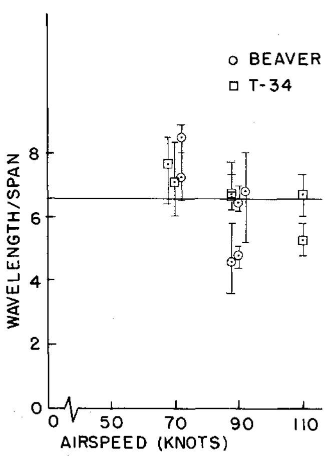


Fig. 5 Vortex instability wavelength.

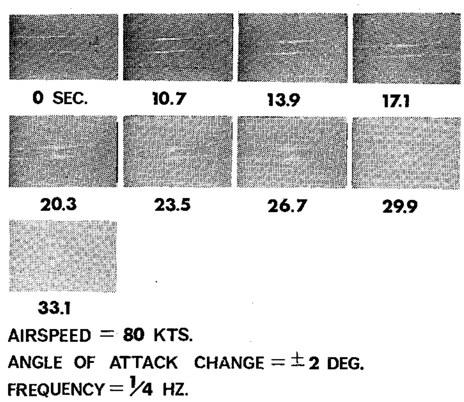


Fig. 7 Photographs of vortex core dissipation for changes in angle of attack.

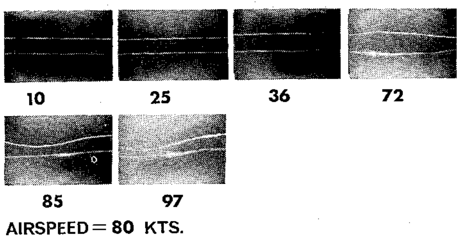
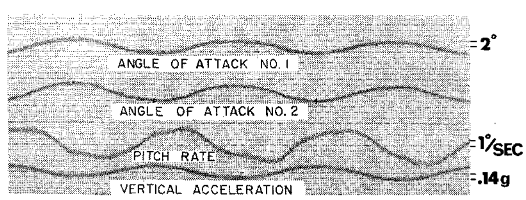


Fig. 8 Photographs of vortex core dissipation for steady flight.

Figure 8 shows the results of a test for steady level flight conducted approximately half an hour later for comparison. The comparison of these results shows that the disturbances produced by oscillations of the aircraft excited an instability along the vortex wake and resulted in the dispersion of the vortex wake in approximately half the time required for steady flight dispersion. Increasing the variation of angle of attack to ±4° resulted in an additional decrease in dissipation time; however, a ±4° change in angle of attack was considered to be excessive and of little practical importance. Changes in angle of attack of less than ±2° were very difficult to produce and very difficult to repeat. These attempts indicated however, that a smaller change in angle of attack would probably be sufficient to excite the instability. A typical time history of the changes in angle of attack, pitch rate and vertical accelerations at an angle of attack change of ±2° and at a frequency of ¼ Hz are shown in Fig. 9. It can be seen in Fig. 10 that for the DHC-2 airplane, variations in angle of attack of ±2° at an airspeed of 80 knots and an altitude of approximately 1000 ft resulted in changes in the lift coefficient below stall and above zero-lift conditions.

Results obtained for a frequency of ½ Hz show that the vortex wake dissipation time was between that obtained for ¼ Hz and that obtained for steady-state flight: approximately 45 sec. Still photographs taken for this flight condition were not of sufficient quality for reproduction; however, motion picture film showing these results is available. Results obtained for a frequency of ⅛ Hz shown in Fig. 11 indicate no reduction in dissipation time when compared to steady flight test results. For this series of flight tests, the dissipation time, by comparison of Fig. 11 and Fig. 8, was greater than that for steady flight.

Repeated flight tests on different days produced similar results. The vortex dissipation time for the steady flight tests varied from 1 to 2 min. The dissipation time observed when the angle of attact was varied at a frequency of ¼ Hz showed a reduction of approximately one-half of the steady dissipation time. In addition, comments from the pilot in the chase aircraft following in the wake of the oscillating aircraft indicated that the wake turbulence was reduced to a mild, random-type atmospheric turbulence. These results show that the critical or optimum frequency for the DHC-2 airplane is approximately ½ Hz and that oscillations of ±2° or less in angle of attack are sufficient to excite vortex instability. These results also indicate that an optimum or critical frequency to redistribute the energy concentrated in the vortices to random turbulence could exist for other aircraft with different values of span loading and wing loading.



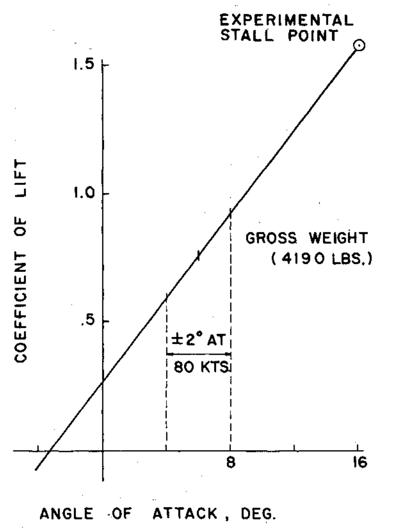


Fig. 10 Variation of coefficient of lift with angle of attack, DHC-2 airplane.

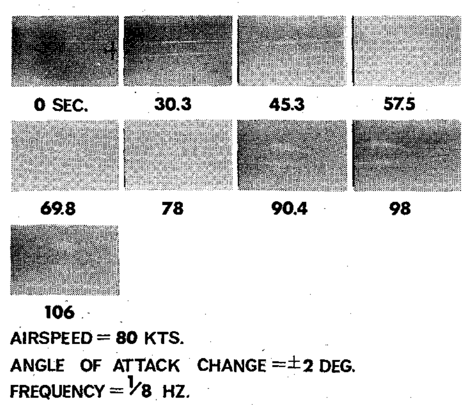


Fig. 11 Photographs of vortex core dissipation for changes in angle of attack.

One confusing result of the tests was the variation in the type of the vortex breakup. As shown in Figs. 7 and 11, the breakups appear in the form of vortex bursting. Enlarged views of the bursting are shown in Fig. 12. Although the critical frequency was calculated based on the wavelength of the sinusoidal wave instability for steady flight shown in Fig. 5, oscillations at this frequency did not appear to accelerate wave formations or the formation

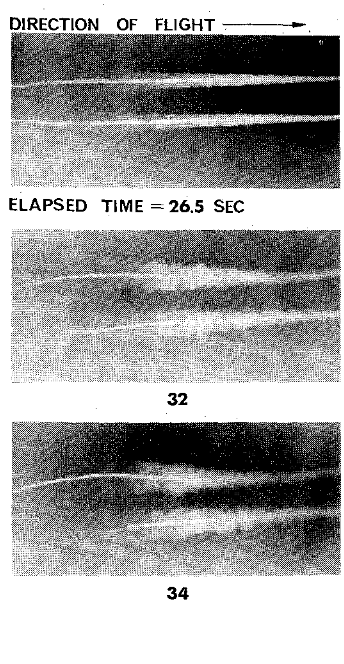


Fig. 12 Photographs of vortex core bursting.

Fig. 13 Typical vortex bursting for oscillations of the DHC-2 airplane, frequency = ¼ Hz, $\alpha = \pm 2°$.

of vortex rings. The results of this investigation show that the wavelength of the Crow-type instability and the wavelength of the vortex bursting instability are the same. This leads to two possible conclusions: 1) The instabilities are related and have identical wavelength values which would be proportional to airplane span; or 2) in the case of the DHC-2 airplane the equivalent wavelengths could be coincidental. Thus, wavelengths of vortex bursting instabilities are not predictable from the results of this investigation for other aircraft. Additional testing using aircraft with large differences in span loading and wing loading are needed to obtain a more detailed understanding of this instability.

Figure 13 shows the location of the vortex bursts as they occurred along the trailing vortices for oscillations of the airplane in pitch. In all cases the initial burst coincided with the minimum angle-of-attack position of the airplane. These results indicate that a disturbance produced by an increasing angle of attack, or wing lift, is necessary to excite this instability.

Concluding Remarks

Results of this flight test investigation have provided additional experimental verification of the existence of vortex wake instability predicted by theory. Experimental results also show that small oscillations of the airplane's angle of attack at a critical frequency accelerate the dissipation of high-intensity vortices.

Since this investigation was conducted primarily to obtain a better understanding of vortex instability, it was not expected that the results would provide a practical solution to the problem of wake turbulence. However, the fact that an instability can be excited by the motion of the aircraft and can cause beneficial vortex interactions could lead to a practical solution to the problem of wake turbulence.

Reference

[1]Crow, S. C., "Stability Theory for a Pair of Trailing Vortices," *AIAA Journal,* Vol. 8, No. 12, Dec. 1970, pp. 2172–2179.