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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Preliminary Investigation of Arc Wing Pitch Characteristics

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Introduction

THE arc wing is distinctive due to a tight, spanwise curvature that describes a semicircular arc over its lateral pitching axis [1]. It has potential for V/STOL aircraft applications because it is uniquely suited to convert the circular slipstream of a large, dual-rotating propeller into lift. The name Arcopter denotes a proposed advanced deflected-slipstream aircraft of this kind [2]; see Fig. 1. But a VTOL concept is viable only if stability and control can be maintained throughout all flight regimes, including transition from takeoff to cruise. The transition regime continues to be the downfall of many VTOL concepts, particularly deflected slipstream types, which fail to thrive due to pitch stability and trim problems [3–8]. The *Arcopter* V/STOL is a special case, where the short-span arc wing is fully immersed in the turbulent slipstream of a large-diameter, dual-rotating propeller. This paper reports the results of an experiment designed to expose wing reactions that would pitch the airframe of a full-size aircraft.

Test Apparatus

The apparatus consisted of a 24-in.-span arc wing suspended in the slipstream of a 30-in.-diam shop fan with a pedestal mount. The wing was free to pivot about a horizontal axis defined by a tubular spar joining the wing tips. See Fig. 2. This test rig was scaled to simulate an actual Arcopter wing/propeller system, that is, the size of the fan disc with respect to the wing was consistent the proportions of a 300-kt Arcopter V/STOL intended for general aviation. The dual objectives of the experiment were 1) to document the pitch stability of the rigid arc wing in the turbulent slipstream of the fan, and 2) to shift the wing fore and aft incrementally with respect to the pitch axis, in order to observe changes in the pitch trim point, that is, the angle of attack at which the wing stabilized in the slipstream of the fan. The pitch axis was the centerline of the free-rotating tubular spar seen in Fig. 2. Adjustable counterweights bolted to the wing tips made it possible to offset the weight of the plastic wing, so that the system could be perfectly balanced before each test run. The counterweights insured that the wing would respond only to aerodynamic tendencies during tests.

To measure the trim point angle of attack, a dial and indicator were fabricated. The dial was bolted to the fixed yoke while the indicator needle was clamped to the rotating spar. Before each test run, the indicator needle was adjusted to be parallel to the center-section chord line of the wing, using the protruding wing tip stick as a fixed reference. Note in the Fig. 3 tip detail the series of 0.188-in.-diam (3/16 in.) holes drilled in the wing tips to allow shifting of the wing with respect to the pitch axis. Center-to-center spacing of the holes was 0.25 in.

The location of the free-turning pitch axis was fixed with respect to the fan disk, and remained in the same spot for all runs. The wing tip chord geometric center provided the reference for gauging the shift. The range of adjustment was from 3.75 in. aft of the pivot point to 0.25 in. ahead of the pivot point. The arbitrary sign convention for

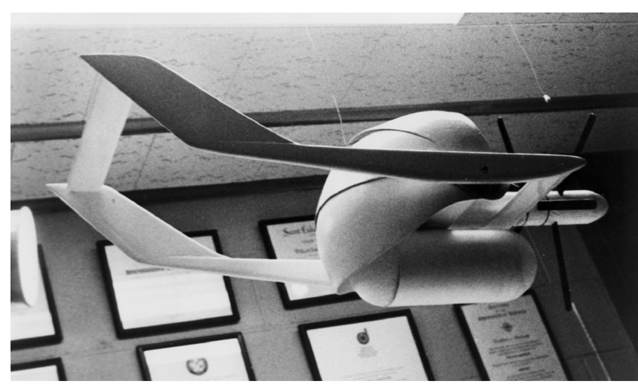

Fig. 1 Arcopter VTOL static model, flaps extended.

Fig. 2 Pedestal fan and arc wing support structure with angle-of-attack meter.

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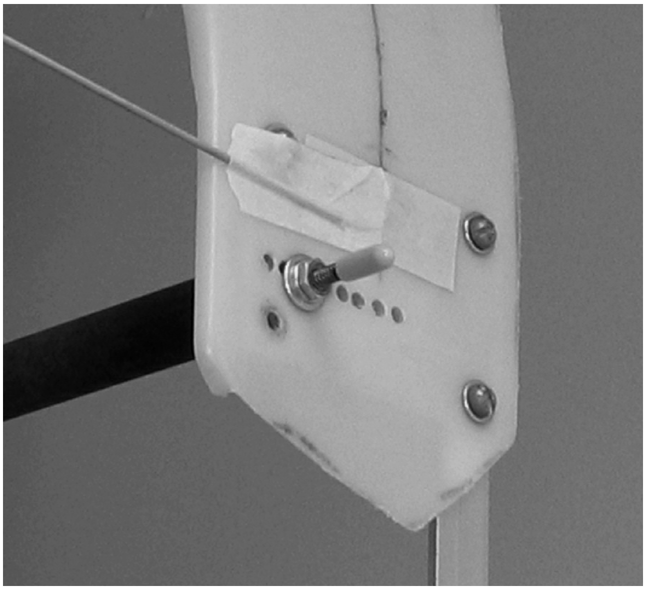

Fig. 3 Wing tip detail with holes for incremental shifts.

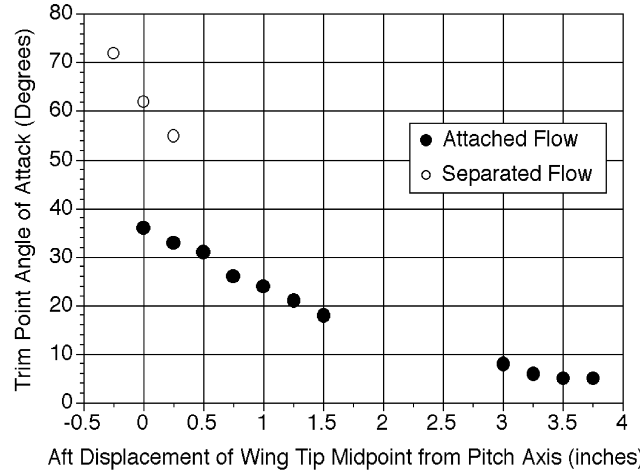

Fig. 4 Trim point angle of attack vs wing location.

these tests was that placements of the wing rearward of the pivot point would have a positive designation whereas shifts ahead of the pivot point would have a negative designation.

Experimental Method

Once the wing was secured to both ends of the tubular spar through the selected tip plate holes, the counterweights were adjusted to balance the freely pivoting wing/spar assembly. The exact distance between the geometric center of the wing tip chord and the center of the rotating spar was recorded. Then the 30-in. fan was switched on. As soon as the wing assumed a stable, zero-pitching-moment equilibrium, the airfoil center-section angle of attack, as indicated by the needle clamped to the tubular spar, was recorded. This stable angle will be referred to as the "trim point" throughout this report. Owing to the careful adjustment of counterweights, use of the airfoil chord reference stick, and large angle-of-attack meter, the error in determining the trim point for a given setup was small, on the order of $\pm 1°$. Yarn tufts were added for some runs to characterize the airflow.

Results and Discussion

Wing Location and Trim Point

Measured pitch trim point angles were plotted as a function of the distance of the wing tip chord midpoint from the pitch axis, as defined by the longitudinal centerline of the wing spar. The graph is presented in Fig. 4. In accordance with the sign convention, displacements of the wing tip chord centerline aft of the pitch axis are given increasingly positive values. Shifts of the tip chord centerline forward of the pitch axis are given a negative sign. Each marker symbol in Fig. 4 represents a stable equilibrium with zero pitching moment. There seemed to be a $+5°$ asymptotic limit to the "attached flow" trend in the low angle-of-attack regime, because the same result was gotten for both the $+3.50$ and $+3.75$-in. stations. But it was demonstrated that the wing could be stabilized in pitch, throughout a broad angle of attack range (from $+5°$ to $+36°$), by shifting the wing fore and aft within a distance corresponding to about $1/3$ of the wing's maximum chord.

Note that two distinct trim points were found for tests at two stations close to the pitch axis, the $+0.25$-in. station and the 0.00-in. station. Testing at the 0.00-in. station with tufts installed revealed that for the $+36°$ trim point, the airflow, though turbulent, seemed to remain attached. If the wing were pushed back beyond about $+40°$, the tufts became random and disorganized, indicating completely separated flow. In that case, the wing would restabilize at $+63°$. Based on tuft observations, the conclusion was reached that there were two self-sustaining dynamics in operation, each resulting in a zero-pitching-moment trim point: 1) a lift-dominated force balance sustained by attached flow, and 2) a drag-dominated force balance dictated by separated flow. Mode 2 could be called "parachute mode." The lift-dominated dynamic seemed to have the upper hand with the wing at the $+0.25$-in. station, while the drag-dominated dynamic had the upper hand with the wing at the 0.00-in. station. With the wing shifted full forward to the -0.25-in. station, no trim point with attached flow could be found. There was only a parachute mode with a trim point of $+72°$. While not a specific objective of these tests, the arc wing also exhibited some degree of yaw stability at each of the various stations. However, the main conclusion from this phase of the experiment was that the pitch-stable trim point of the rigid arc wing could be varied from $+5$ to $+72°$ by shifting the wing fore and aft with respect to the pitch axis, by a distance that corresponds to $1/3$ of the maximum chord.

Flow Visualization

While the test stand was not instrumented to measure lift and drag, yarn tufts gave some indication of the nature of airflow over the wing at various angles of attack. See Figs. 5–7. Note that in each of the figures, the fan appears to be stationary due to the camera flash. It was actually turning at about 1,167 rpm in all three pictures.

In the case of Fig. 5, a lift-dominated force balance kept the angle of attack relatively low ($+5°$). Note the apparent, well-behaved flow over the top, as indicated by the tufts. In Fig. 6, the wing has been made to stabilize at a high angle of attack by shifting the wing forward 3.75 in. with respect to the pitch axis. This position is the 0.00-in. station, where the dashed centerline of the wing tip chord is exactly coincident with the pitch axis. The needle indicates $+36°$. Note that the tufts seem to indicate attached flow over the top. Based on this reading of the tufts, it appeared that the arc wing had attained a high-lift stance, without the extension of a flap. Nonetheless, the pitching moment remained at zero, with retention of positive stability.

Figure 7 shows a further extension of the realm of stability. Note the apparent flow separation in Fig. 7. Here the tufts are random and disorganized, in contrast to the preceding figure. In Fig. 7, the wing remains at the 0.00-in. station, however, it had been forcibly rocked back (by hand) beyond $+39°$, causing flow to separate. Decreased lift and increased drag then drove the wing to its alternate trim point $+62°$ as the photo was taken. Yet static stability was maintained. Note also that the center of lift of the system (also coinciding with the tubular spar) remained in exactly the same location in Figs. 5–7.

Arc Wing Active Incidence Control

Based on the consistent response of the free arc wing to the discreet, incremental shifts, it was decided to modify the model to allow the wing to be shifted smoothly fore and aft within a 4-in. continuum, by remote control, while still free to tilt in the slipstream

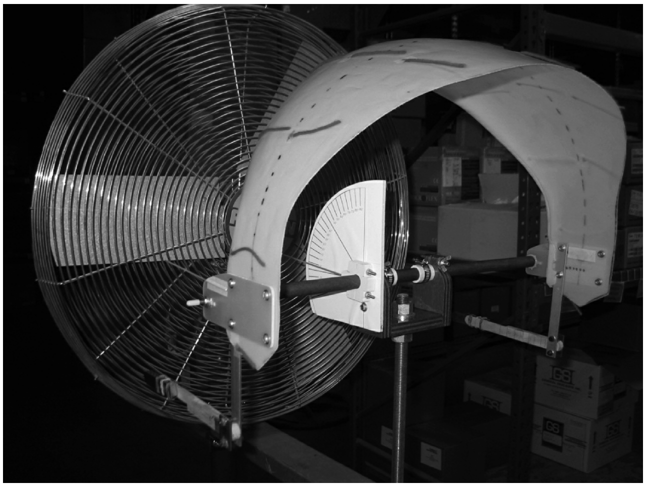

Fig. 5 Arc wing stabilized at +5°, attached flow.

Fig. 6 Arc wing stabilized at +36°, attached flow.

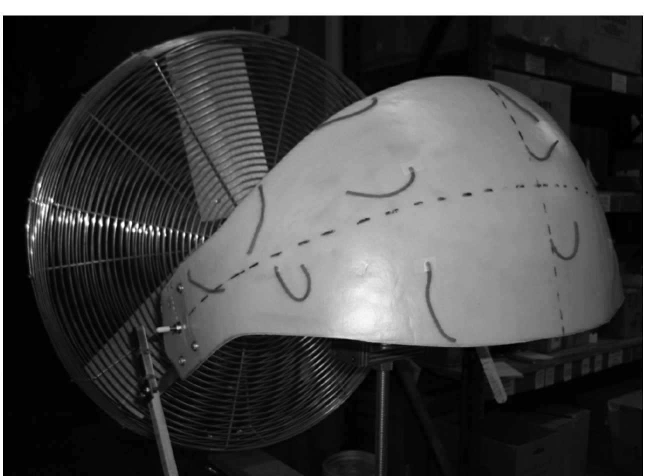

Fig. 7 Arc wing stabilized at +62°, separated flow.

of the fan. The idea was to attempt to manipulate the aerodynamic force balance in order to tilt the wing at will, thereby establishing positive control over the angle of incidence with respect to the thrust axis.

To accomplish the necessary smooth fore–aft shifts of the wing with respect to the pitch axis, a simple track-and-roller system was incorporated into the wing tips, consisting of a pair of mini-ball-

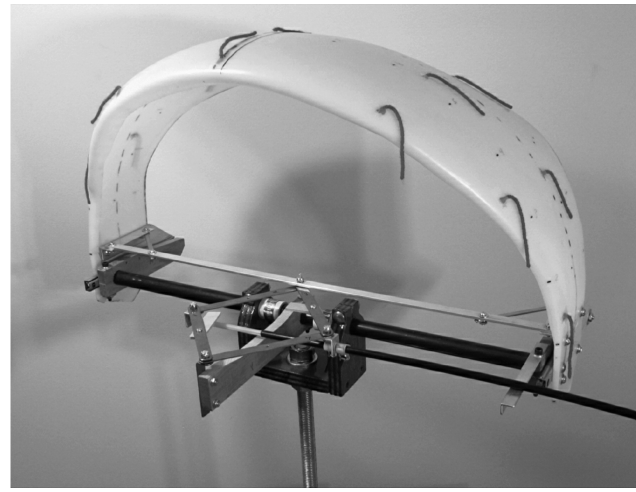

Fig. 8 Arc wing fitted with remote shift mechanism.

Fig. 9 Setup for arc wing incidence control tests.

bearing drawer slides. The remote actuator was a light-duty push–pull tube assembly. It was connected to a scissors linkage, which converted the lateral push–pull input into fore–aft travel for the wing. The renovated model appears on static display in Fig. 8 with the yoke tilt bearings locked. Visible in Fig. 8 is the protruding center clamp block that served to anchor the forward (fixed) end of the scissors linkage. Total motion was 4.00 in. The ball-bearing slides worked well, and only minimal opposing forces on the concentric push–pull tubes were required to shift the wing. There were sufficient clearances to allow the wing to tilt up to +90°. The push–pull tube assembly was close enough to the center of rotation so as not to inhibit the pitch response of the wing when the fan was running.

Note also the absence of the counterweights in Fig. 8. It was decided to remount the wing model on its side to neutralize gravitational forces on the wing and obviate the need for counterweights. The push–pull tubes would then extend downward out of the slipstream, where a kneeling operator could run the apparatus from a distance. Figure 9 shows the completed setup. When the fan was turned on and the tilt bearings were unlocked, the wing did indeed seek its pitch equilibrium as before, but it did so with a bit more alacrity, owing to a reduced moment of inertia by the elimination of the counterweights. The wing responded to the new control as expected, with the wing stabilizing at low angles of incidence when shifted rearward and stabilizing at higher angles of incidence when shifted forward. The wing always rocked back to parachute mode when shifted full forward. However, only a slight aft shift of the wing (1.0 in. aft of the forward limit) was required to effect immediate recovery. The testing also revealed that the control forces required to manipulate the wing were low. If one released the controls in an intermediate position, the wing would drift slowly either toward full aft, stabilizing at $+5^\circ$, or drift slowly toward full forward, stabilizing in parachute mode. It was unexpected to find that the wing would sometimes drift forward when the controls were released, because that direction opposed the flow from the fan. It should be mentioned that on a full-scale aircraft with a lightweight, rigid arc wing structure, fore and aft shifts would be done by electric or hydraulic actuators housed in each wing tip. There would be no need for the secondary spar joining the wing tips.

Conclusion

The rigid arc wing proved to be statically stable in pitch in the slipstream of the propeller [9]. Furthermore, it was demonstrated that the stable trim point could be varied incrementally, by shifting the wing fore and aft, with respect to the pitch axis. The arc wing seemed able to maintain attached flow in the propeller slipstream at angles as high as 36°, with continued pitch stability. Two trim points were found in the high angle of incidence regime, one lift dominated, one drag dominated. It appears feasible to devise a track-and-roller system to shift the wing tips of a full-size arc wing aircraft, enabling the pilot to rotate and lock the wing to the optimum angle of incidence for the desired flight regime, whether it be takeoff, transition, cruise, or deceleration. Computational fluid dynamics, supplemented by wind tunnel tests, are needed to quantify and optimize the lift, drag, and moment coefficients of the arc wing.

References

[1] Dickey, E. D., and Sivier, K. R., "Analysis of Non-Planar Wings with Constrained-Span Design Applications," *AIAA 9th Applied Aerodynamics Conference*, Sept. 1991, AIAA Paper 91-3317.

[2] Bertelsen, William D., "Introduction to the Arcopter Arc Wing," *Science and Technology of Low Speed and Motorless Flight*, edited by P. W. Hanson, NASA Conference Publication 2085, Part 1, NASA Langley Research Center, Hampton, VA, 1979.

[3] Kuhn, Richard E., and Draper, John W., "Investigation of Effectiveness of Large-Chord Slotted Flaps in Deflecting Propeller Slipstreams Downward for Vertical Take-Off and Low-Speed Flight," NACA TN 3364, Jan. 1955.

[4] Kuhn, Richard E., "Investigation of the Effects of Ground Proximity and Propeller Position on the Effectiveness of a Wing with Large-Chord Slotted Flaps in Redirecting Propeller Slipstreams Downward for Vertical Take-Off," NACA TN 3629, March 1956.

[5] James, Harry A., Wingrove, Rodney C., Holzhauser, Curt A., and Drinkwater, Fred J., III, "Wind-Tunnel and Piloted Flight Simulator Investigation of a Deflected-Slipstream VTOL Airplane, the Ryan VZ-3RY," NASA TN D-89, Nov. 1959.

[6] Turner, Howard L., and Drinkwater, Fred J., III, "Some Flight Characteristics of a Deflected Slipstream V/STOL Aircraft," NASA TN D-1891, 1963.

[7] Fink, Marvin P., "Full-Scale Wind-Tunnel Investigation of the VZ-5 Four-Propeller Deflected-Slipstream VTOL Airplane," NASA TM SX-805, 1963.

[8] Bertelsen, W. D., and Bertelsen, W. R., "History of Deflected Slipstream VTOL Aircraft," *Vertiflite Magazine*, American Helicopter Society International (submitted for publication).

[9] Bertelsen, W. D., "Preliminary Investigation of Arc Wing Pitch Characteristics," *AIAA 5th Aviation Technology, Integration, and Operations (ATIO) Conference*, 2005; AIAA Paper 2005-7440.