BIRD AERODYNAMIC EXPERIMENTS

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INTRODUCTION

The senior author's research in the area of skin friction reduction by compliant coatings led him to investigate the aerodynamic properties of bird feathers. Three separate experiments performed during the last several years are reported in this paper. The experiments are: (1) relation between the compressive modulus of bird feathers and bird maximum level flight speed (2) the effect of flexible slotted-tip feathers on the wing-wake vorticity and (3) the effect of owl leading edge barbs on lift and drag characteristics of wings.

FEATHER COMPLIANCY AND FLIGHT SPEED

Ornithologist Dr. George Sutton showed the senior author through the University of Oklahoma Bird Range several years ago to point out the unique characteristic of various birds. The senior author noted, upon touching the birds and inquiring about their flight speeds, that there appeared to be a correlation between the stiffness of the bird feathers and their flight speeds. The birds which flew slow seemed to have soft feathers while those which flew fast seemed to have hard feathers. To determine the validity of this hypothesis it was decided to measure the compressive modulus of bird feathers by measuring the deflections of a small weight placed on their breast and then plotting the compliancy versus level flight speed.

Figure 1 is a sketch of an apparatus that was built to measure the stiffness of bird feathers. Basically, it was a vernier caliper accurate to within 0.01 cm, and a 12 volt ac electromagnet (E) attached at the upper fork and a piece of plexiglass with a hole to guide and hold a small weight (D). Three rough adjustments (J, G, and N) and three fine adjustments (I, F, and O) were installed for positioning the bird pan (B), the electromagnet (E) and the spot light (K). Two switches were installed to operate the electromagnet and the spot light.

Three different weights were constructed of cylindrical steel shells filled with balsa wood. The weight/contact area ratio (F/A) for each weight was 2.06 gm/0.54 cm^2, 2.97 gm/0.54 cm^2, and 1.53 gm/0.903 cm^2. Since there was a wide range of feather stiffness among the birds it was necessary to select a weight which was not too heavy or too light.

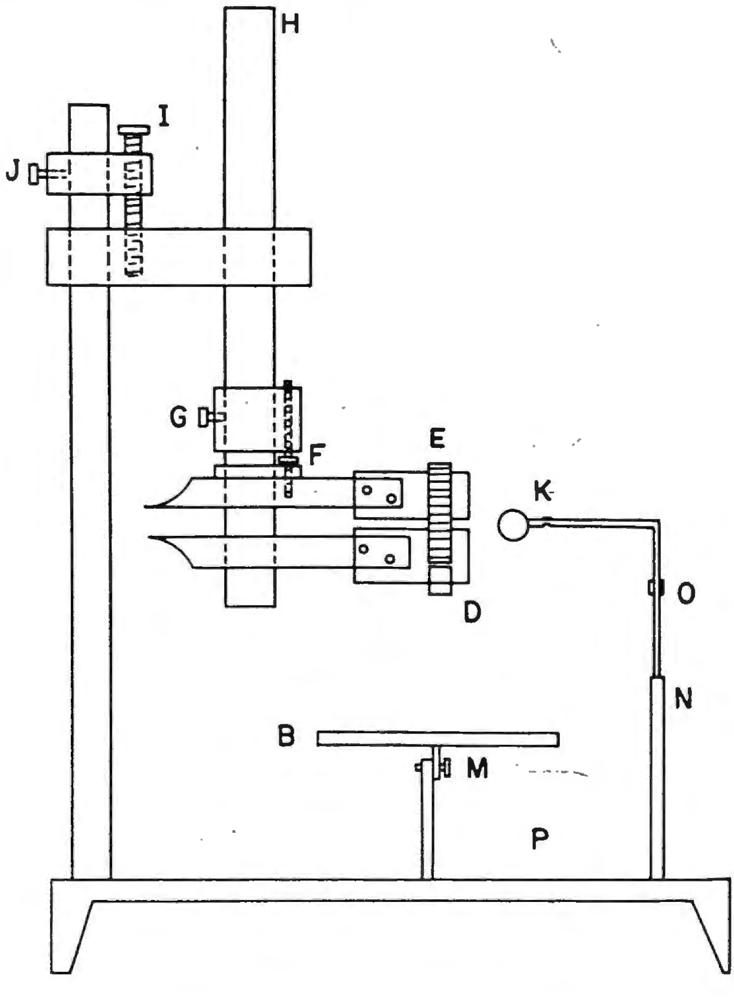


Figure 1. Bird feather compressive modulus rig.

The birds used in this study were all dead and stuffed. Each bird was laid flat on his back on table (B). An appropriate weight was selected and gently laid upon the chest (about two fifths of body length from the beak). The weight was depressed gently. If the weight completely compressed the feathers the weight/area ratio of the weight was too heavy for the bird and another weight was chosen that gave a moderate deflection. The electromagnet was turned on and the weight was then placed into the plexiglass hole and held there by the electromagnetic field. Adjustments were made so the weight was just barely touching the bird. The spotlight (E), was leveled to the interface between weight (D) and the chest to assist in this adjustment. The indicated reading on the vernier was recorded. Next the electromagnet was turned off and the weight dropped on the chest feathers. The fine adjustment (F) on the calipers was adjusted so no light passed between the bottom of the electromagnet and the top of the weight. The new vernier reading was recorded. The difference between the first and second reading gave the deflection of the chest feather. This procedure was carried out on ten different birds.

The feather compressive modulus was defined to be the applied pressure, F/A divided by the relative deflection of the feathers $(\Delta s/s)_f$. s is the thickness of the bird's chest feathers. Most of the bird flying speed estimates came from Storer (1948) and Cooke (1937). Figure 2 presents the feather compressive modulus plotted versus maximum level flight speed of the birds. Some data points show a horizontal spread due to uncertainty in the maximum level flight speed of particular species. In general high compressive moduli were associated with high speeds. A line drawn through the data has a 2:1 slope indicating that the compressive modulus was proportional to the velocity squared. This suggests that the stiffness of bird feathers is proportional to the maximum dynamic pressure, $\frac{1}{2}\rho V^2$, where ρ is the air density and V is their maximum level flight speed. It is known from aerodynamic theory that the aerodynamic pressure found on surfaces is proportional to the dynamic pressure. The implication is that the shape of a flying bird does not become unduly distorted but remains aerodynamically smooth. This is because the surface pressures on their body feathers are never large enough to compress and distort the feathers to any large degree.

WING TIP VORTICITY MEASUREMENTS

Figure 3 shows the slotted wing tips of a hawk and an eagle. Cone (1959) speculated that the slotted tip feathers of hawks, eagles and buzzards may be responsible for their excellent soaring ability. None of these birds have the high aspect wing of the gull which is also an excellent soarer. Cone (1959) felt that

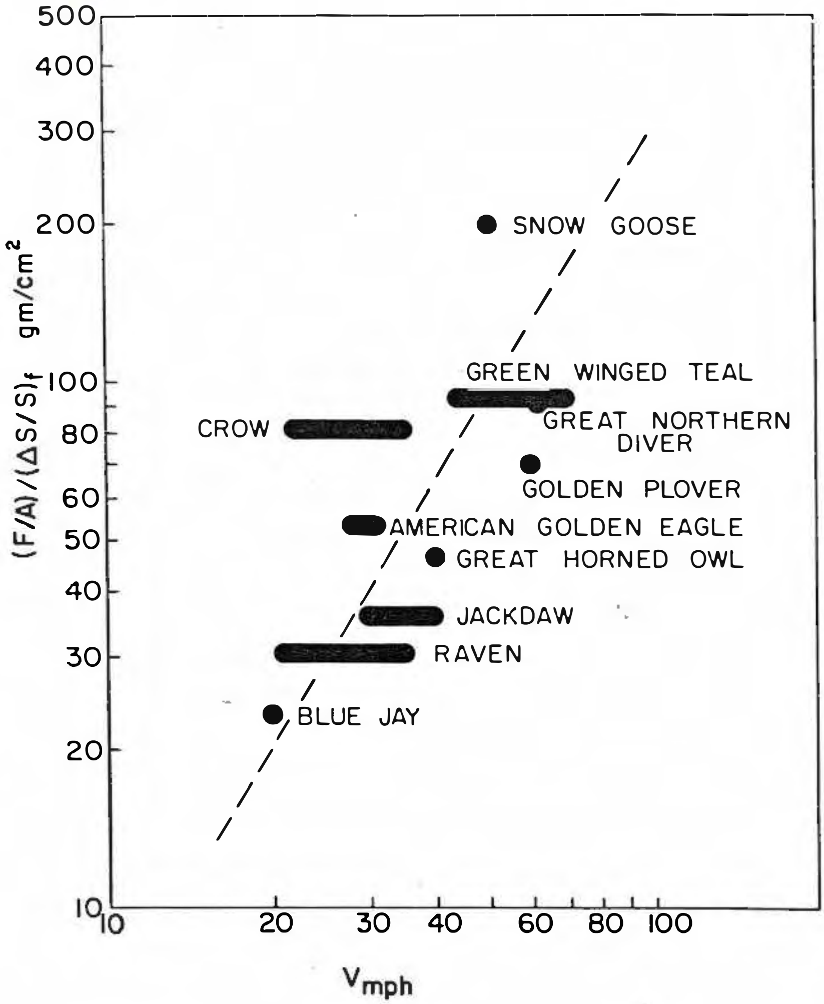


Figure 2. Feather compressive modulus vs. flight speed.

the flexible-slotted-tips which bend upward during flight may alter the trailing vortex pattern in such a way so as to alter the induced-drag due to lift. With this in mind tests were performed in the University of Oklahoma wind tunnels to determine the effects of flexible-slotted-tips on the trailing vortex pattern.

A rectangular planform (7 inch chord by 42 inch span) wooden wing with an NACA 2418 airfoil section was used in the tests. Five pinion feathers from the wing tip of a wild Canadian goose were attached to each wing tip. The feathers were approximately eight inches long and 1.5 to 1.25 inches wide. The feather shafts were glued in holes drilled in the wing tips. The incident angles (measured with respect to the chord line of the wing) ranged from approximately ten degrees at the leading edge feather to zero degrees at the trailing edge feather.

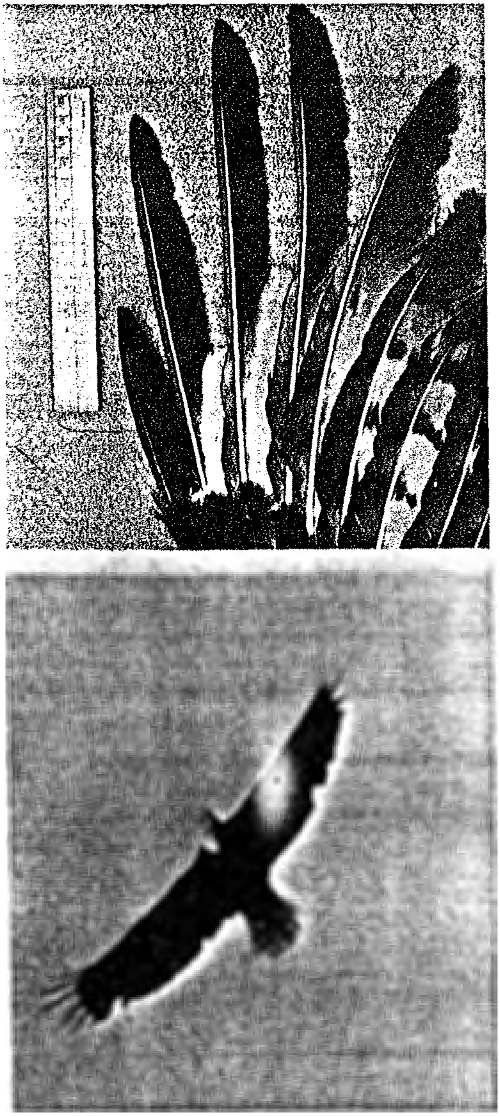


Figure 3. Slotted wing tips of an eagle and hawk.

Tests were run in the closed-circuit Mark I tunnel which has a 4 ft. by 6 ft. quasi-elliptical cross-section. The tunnel is powered by a 450 hp electric motor with variable propeller pitch and has a top speed of 200 mph. Tests were run at 49 ft/sec, 58 ft/sec, and 70 ft/sec.

Vorticity behind the wings were measured with an Aero Engineering Assoc. Inc. (University Park, Penn.) vorticity meter which was powered by a 4.5 volt dc source.

Figure 4 shows the vorticity twelve inches (1.7 chord lengths) behind the slotted-wing tip and a plain-wing tip (rectangular tip) at a speed of 58/sec and eight degrees angle-of-attack. The outer edge of the slotted-wing tip was seven inches from the tunnel wall. When the eight inch tip feathers were removed, the plain-tip was fifteen inches from the tunnel wall. Figure 4 indicates there were at least three distinct vortex cores behind the slotted-wing tip. There were probably two others (five tip feathers) but they were not intercepted by the vortex meter as it swept along a line twelve inches behind and 3/4 inch above the wing. Behind the plain-tip one distinct vortex core was detected. The plain-wing tip had a maximum vorticity of approximately an order of magnitude greater than the slotted-wing tip, 1500 rad/sec versus 360 rad/sec.

Figure 5 shows the maximum vorticities measured twelve inches behind the slotted-tip and plain-tip for several wind tunnel speeds. Only two low-speed data points are presented for the slotted-wing tip. At speeds much above 60 to 70 ft/sec the feathers

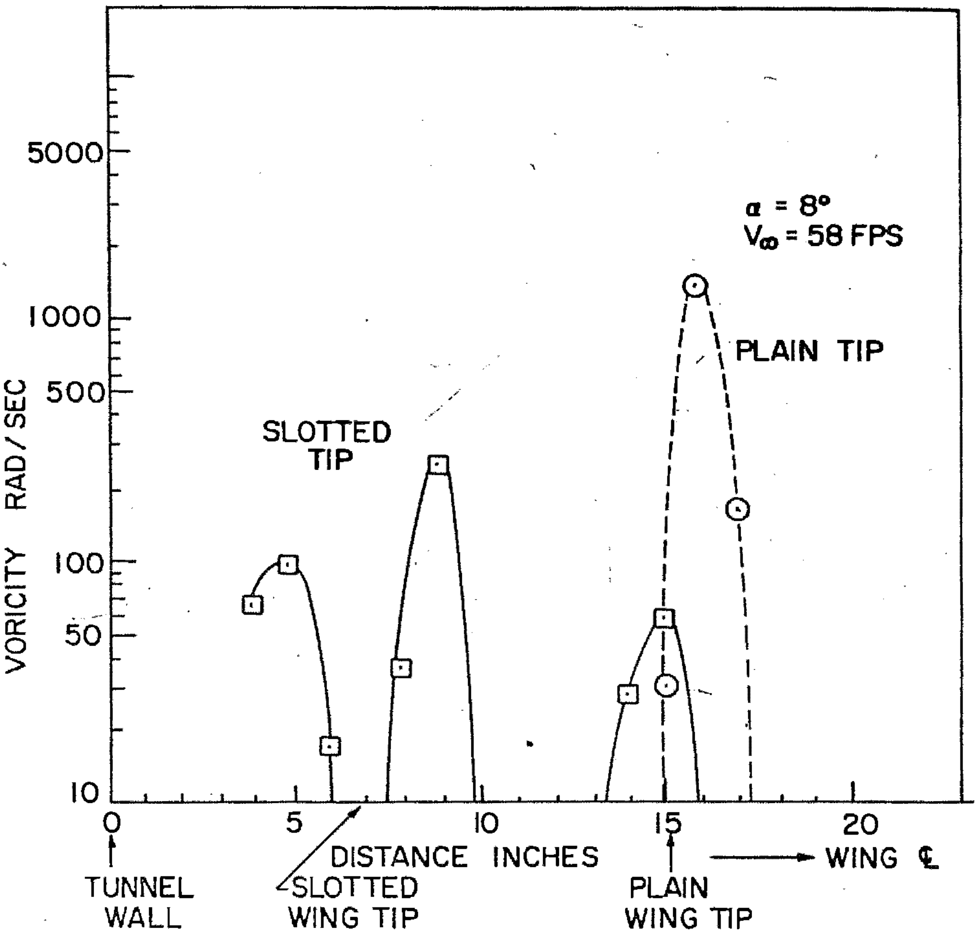


Figure 4. Vorticity near plain and slotted tips.

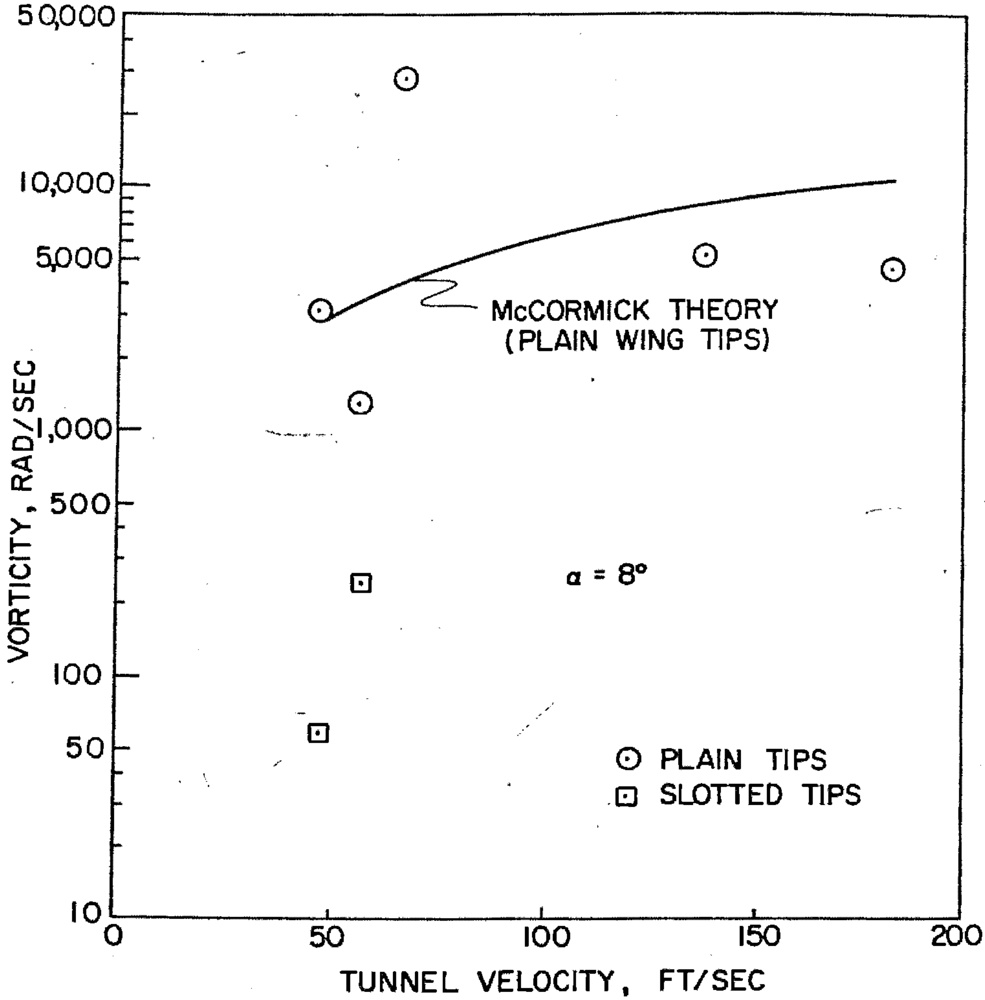


Figure 5. Maximum vorticity behind wing tips.

suffered severe deflection in the downstream direction and therefore no tests were performed on them at speeds above 58 ft/sec.

The solid line in Figure 5 is the theory of McCormick (1971) for maximum vorticity behind wing tips. McCormick (1971) derived the following equations for the vorticity in the vortex core at distance of Z feet behind a wing (with plain-wing tips).

$$\xi = \frac{34\ C_L\ V}{C_o C_{l_o} (1 + 0.00063\ Z/\overline{C}\ C_L)} \quad \text{rad/sec} \qquad (1)$$

where V = free stream velocity, ft/sec

C_L = wing lift coefficient

$\overline{C}$ = mean chord length, ft.

C_{l_o} = midspan section lift coefficient

C_o = midspan chord length, ft

At eight degrees angle-of-attack, C_L was measured to be 0.55. For the test wing with plain tips, assuming $C_{l_o} \approx C_L$ and with $C_o = \overline{C} = 7/12$ ft. the theoretical vorticity one foot behind the wing is given by

$$\xi = 58.2\ V \quad \text{rad/sec} \tag{2}$$

This was plotted in Figure 5 and labeled "McCormick Theory". There was considerable scatter of the data but nevertheless equation (2) did offer a fair correlation with the plain-tip data.

Again it can be seen from Figure 5 that the plain tip had vorticities which were an order-of-magnitude greater than the slotted-wing tips. More detailed test data can be found in the Masters Thesis of Belie (1972).

There is the possibility that similar slotted-wing tips used on large aircraft such as Boeing 707s or 747s would reduce the wake vortex hazard that now exists in the vicinity of airports.

OWL BARBS

It is generally accepted among ornithologists that owls generate very little noise in flight. Some have speculated that this quiet flight might be related in part to the barbs that are located on the leading-edge of the most forward primary feather (see Figure 6). Kroeger (1971) measured the noise generated by flying owls and concluded that both the leading-edge barbs (LEBS) and the soft-downy-like compliant surfaces of the wing feathers were the primary mechanisms for reducing the noise due to unsteady lift and the turbulent boundary layer.

Hersh and Hayden (1972) tested an airfoil and a propeller with LEBS in a free jet acoustic wind tunnel. They found that radiated sounds were reduced by the barbs and were very sensitive to the size and location of the barbs. More recently Schwind and Allen (1973) conducted high frequency sound surface measurements

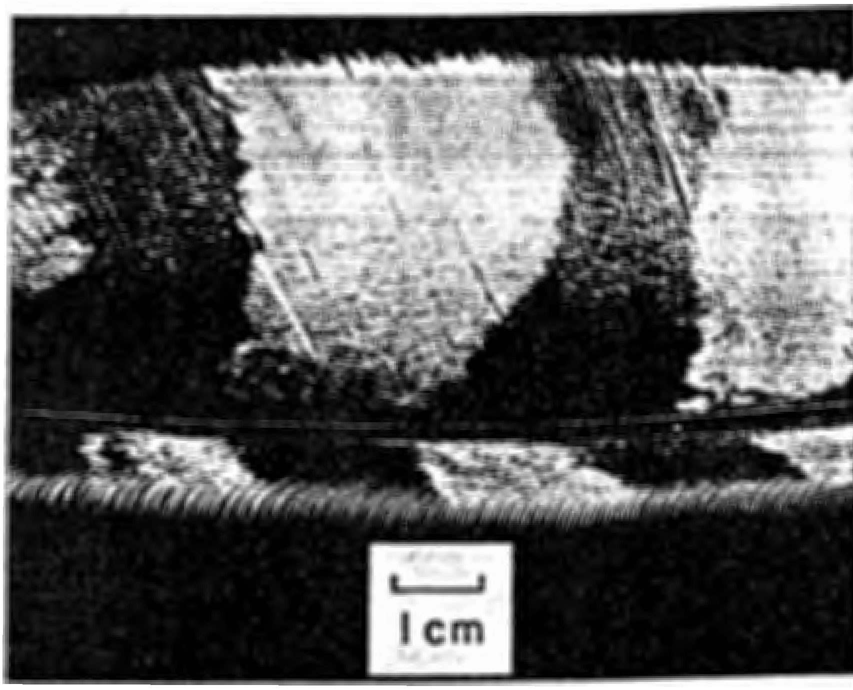
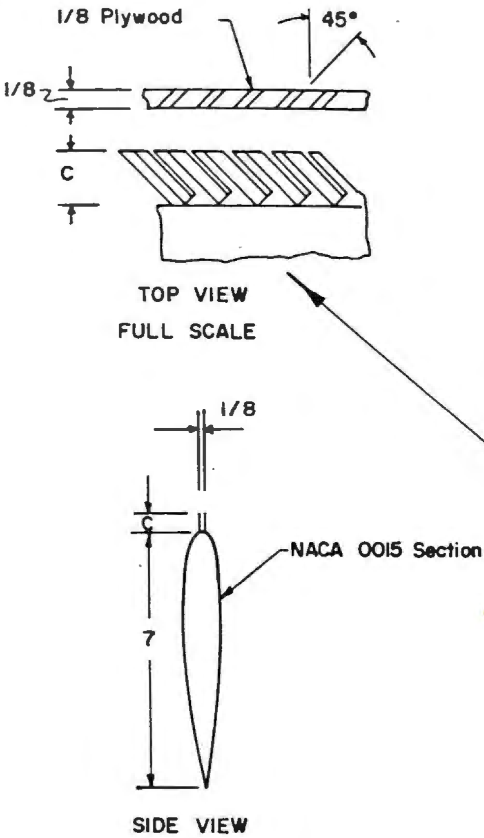


Figure 6. Owl primary feather

on an NACA 63-009 airfoil with and without LEBS. A laminar separation bubble was observed on the basic airfoil, however, the addition of LEBS divided the bubble into segments and reduced the peak rms pressure.

Soderman (1972) tested an NACA 66-012 airfoil for aerodynamic performances with various LEBS and found that by proper design and placement of LEBS an increase in the maximum coefficient of lift could be obtained. One particular configuration placed sligtly behind and below the leading edge, produced a 25% increase in the maximum lift. The purpose of the University of Oklahoma tests was to study the effect of a new type of three-dimensional barbs on the aerodynamic performance of wings.

The 4 ft. by 6 ft. University of Oklahoma subsonic wind tunnel described in the section on Wing Tip Vorticity Measurements of this paper was used for all wind tunnel tests. An NACA-0015 wooden wing (with two imbedded steel spars) of aspect ratio 6 (42 inch span by 7 inch chord) was used in the tests (see Figure 7). The LEBS were modeled after those of the Great Horned Owl (Figure 6). The Great Horned Owl barbs are inclined approximately 45 degrees from the vertical and have an average sweepback angle of about 45^{o} in the horizontal plane. For the wind tunnel model, LEBS were cut from 1/8 inch, 5 ply model-airplain plywood and inserted in the leading edge nose.



Leading - Edge Serrations

S. Spacing	W. Width	C. Chord	No.
.00885	.0043	.0359	1
.00885	.0133	.0359	2
.00657	.00657	.0359	3
.00657	.00885	.0536	4
.0133	.00885	.0536	5
.0179	.0133	.0536	6
.00657	.0133	Varies	7

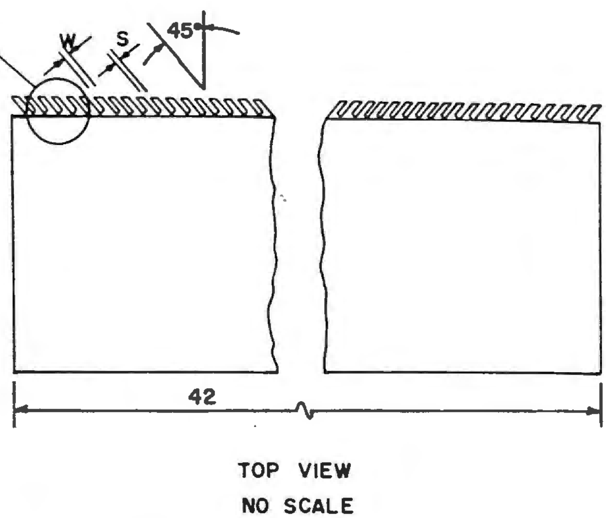


Figure 7. Wind tunnel model

The tests were conducted at 50 mph and 165 mph with corresponding Reynolds numbers (R_N) of 250,000 and 850,000 respectively. Various combinations of spacings, widths and chord lengths of the LEBS were tested. In addition tests were run with the LEBS on the outer 25%, 50% and 75% of the span as well as 100% span tests.

Figure 8 shows the effects of various types of LEBS on the coefficient of lift (R_N = 250,000). The spacing between barbs is 3/64 inch, the barb width was 3/32 inch and the barb chord was a variable. The larger barb chords resulted in lower lift coefficients at small angles-of-attack but higher lift coefficients at larger angles-of-attack. The effect of the LEBS on stall is dramatic. Instead of a sharp drop in lift at the stall angle of 12° (for the plain wing) the LEBS modified the lift to either remain more-or-less constant (up to 25°) or to cause the lift slope to

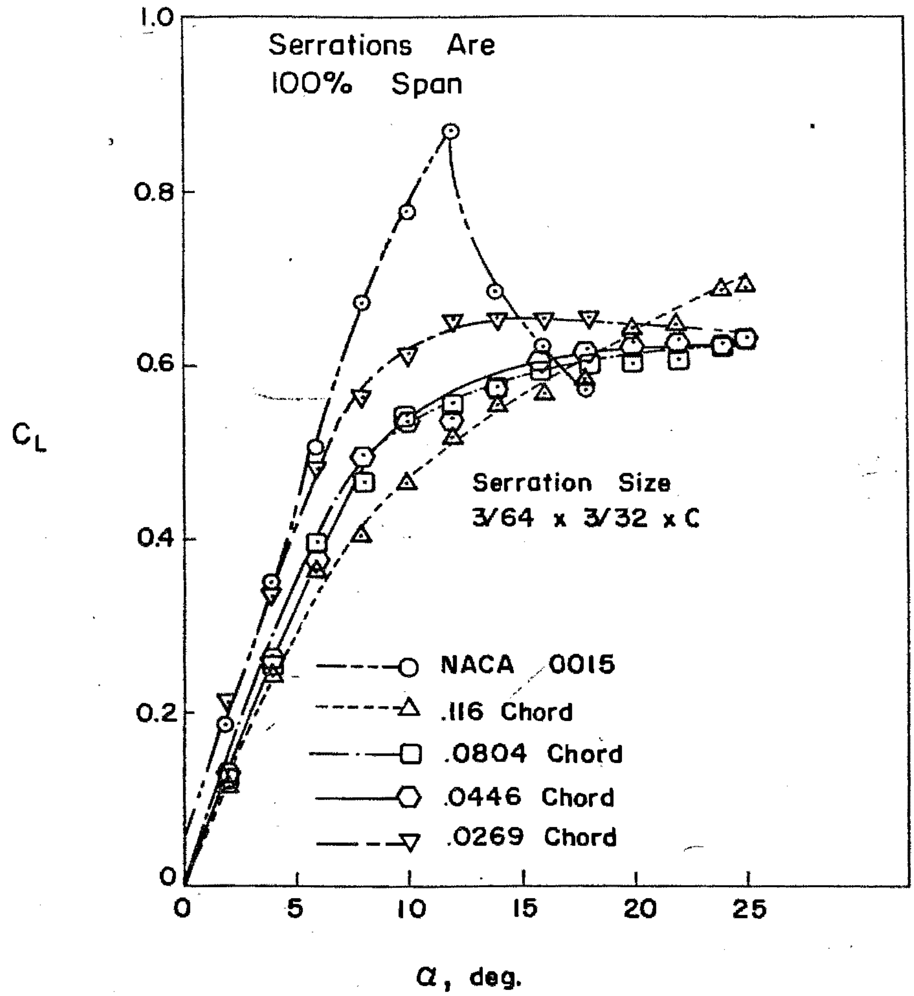


Figure 8. C_L of LEBS -- Wing

roll over to a smaller but still positive value (no stall). Some tests were run up to 45 degrees angle -of-attack and two of the LEBS configurations were found to have higher lift coefficients than the plain wing in this regime. Drag data on the wings indicated that the barbs tended to increase the drag slightly at low angles-of-attack but decrease the drag at angles-of-attack above the original stall angle. For more detailed wind tunnel results, one should see the dissertation of Watson (1973).

Tufts and oil (titanium dioxide and vacuum pump oil) were added to the upper surface in order to determine the visual flow pattern. Figure 9 shows the tuft and oil flow patterns on a wing equipped with LEBS. From Figure 9 it appears that the vortex filaments emanating from the LEBS prevent the occurrance of

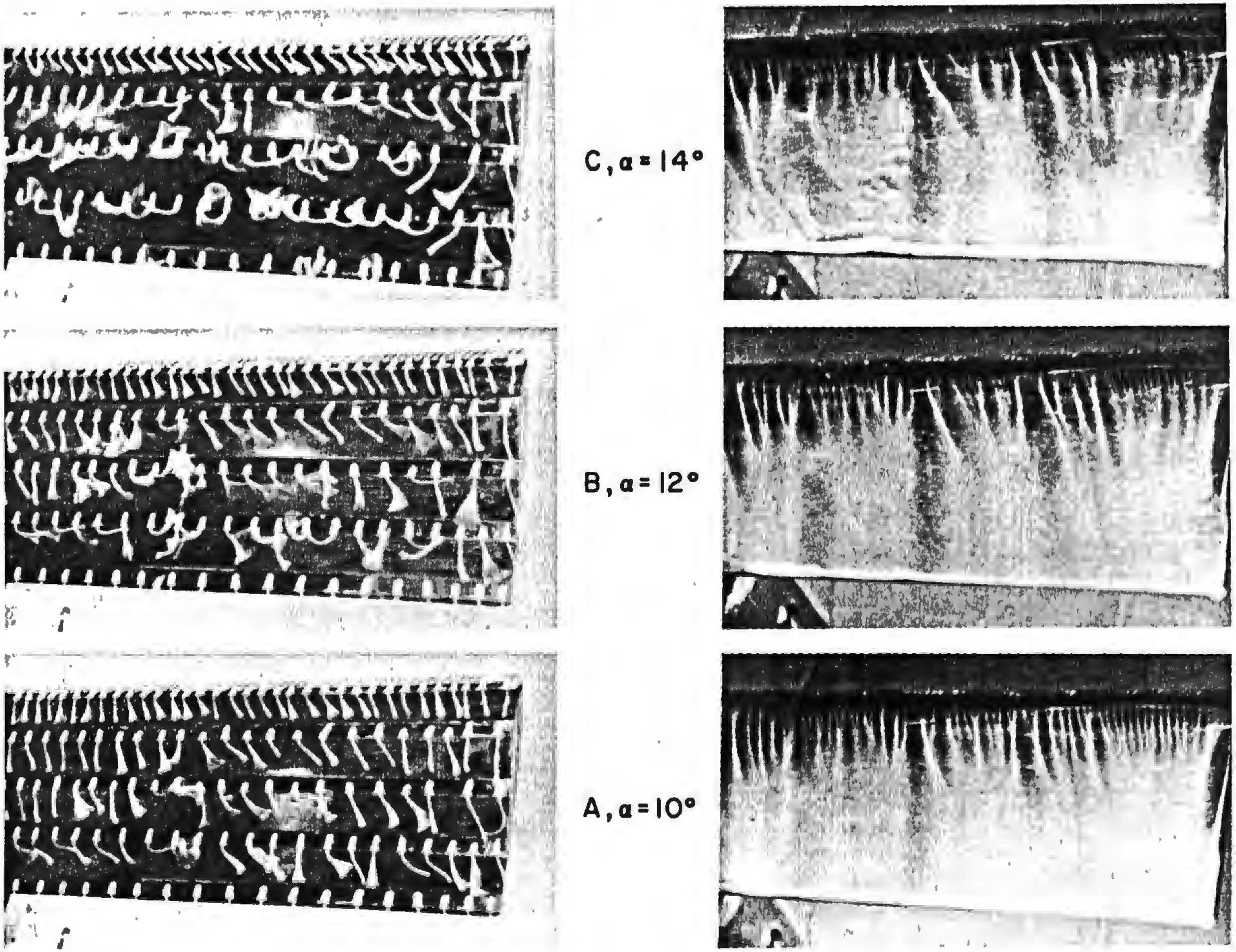


Figure 9-a. Tuft and oil patterns on LEBS -- wing

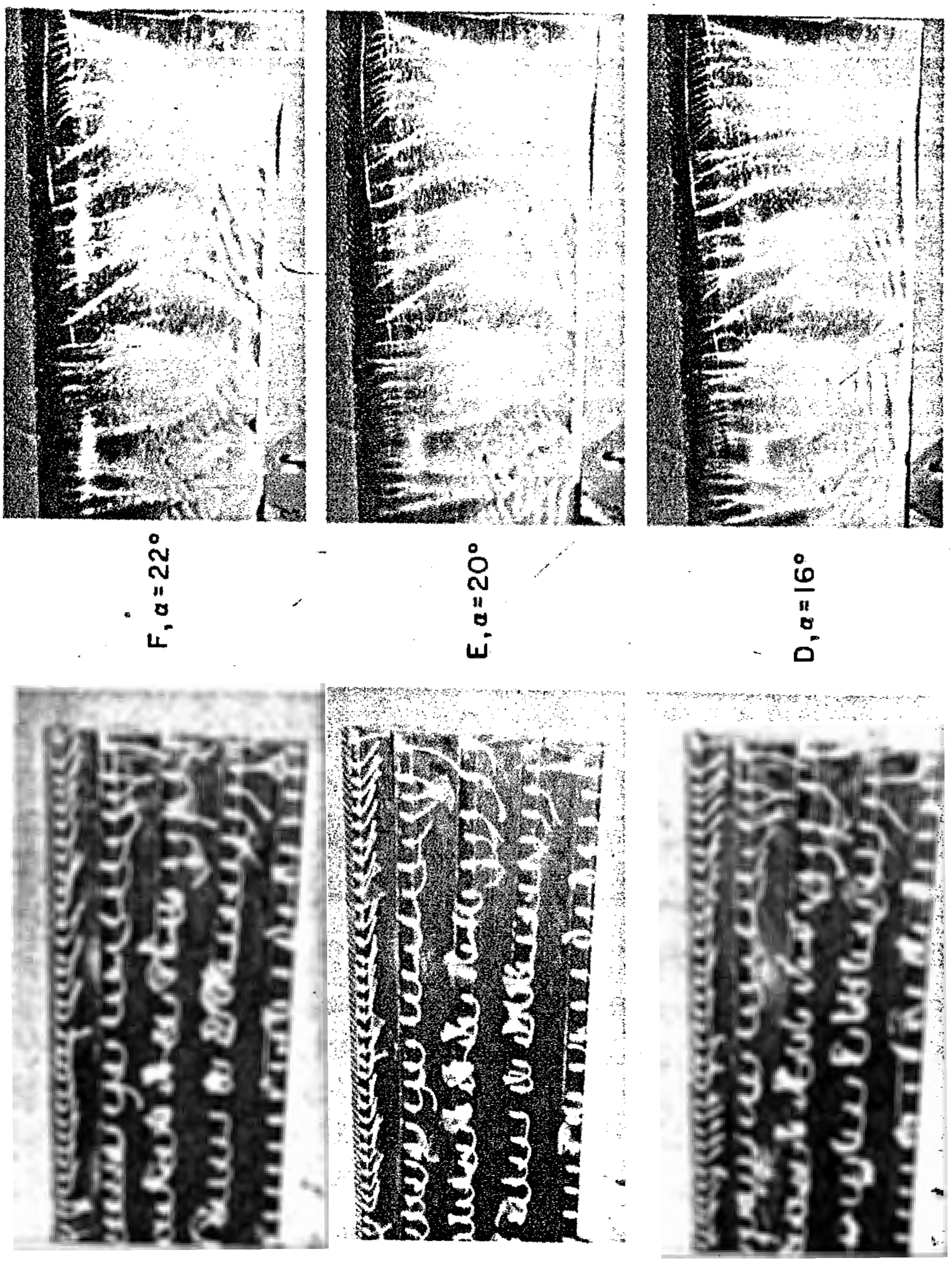


Figure 9-b. (continued)

leading-edge separation but do not affect the initial trailing-edge stall. This probably explains the nonlinear behavior of the lift slope of the LEB wings in Figure 8. The initial trailing edge separation causes the lift curve to "round off" but the LEBS keep the flow attached near the leading edge even at large angles and hence prevent the wing from completely stalling. The tuft and oil flow pictures of the plain wing showed both trailing edge and leading edge stall at approximately 12-14 degrees angle-of-attack.

There is the possibility that the addition of LEBS to some aircraft would reduce the number of stall-spin accidents. Certain types of aircraft used in training pilots have been shown by the FAA to have an unusually large number of stall-spin accidents.

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