Theory, testing & in-flight: put teeth on it and take a bite out of your airplane's stall

Camille Goudeseune
University of Illinois
cog@illinois.edu http://camille-g.com

Adding teeth to your flat-foam airplane's leading edge reduces tip-stalling. It also stabilizes wing rock in harriers. On the flight line, it turns heads, and in the air, it might intimidate others into giving you more room. These pages will show you how a serrated leading edge changes responsiveness, both in the wind tunnel and on actual airplanes. You'll also learn just enough theory to explain it yourself to your flying buddies.

Beyond the stall

Stall is just another word for airflow separation. At small angles of attack, air flows smoothly past a wing to produce much lift and little drag. Lift increases as you keep increasing the airfoil's angle of attack (AoA). Eventually, however, the flow over the top of the wing cannot stay attached to it, and breaks free into large eddies. The wing's lift at that point comes from air slamming into its bottom face, as the airflow above the wing is a chaotic mess.

If we energize the boundary layer close to the wing with small turbulent vortices, we reduce the scale of the chaos. The few giant eddies become many small eddies, and the overall flow follows the wing more closely. Unfortunately, this increases drag and reduces lift when flying at a small AoA, but that hardly matters on an overpowered airplane that rarely flies level. It matters even less when the airfoil is an inefficient flat plate to begin with.

New flat-plate wing designs

Having decided that traditional wing efficiency (the lift-to-drag ratio) didn't matter for flat plates, I sketched three dozen unorthodox wings that might better suit overpowered models. My group narrowed that down to a dozen for testing in the low-speed wind tunnel at the University of Illinois. From that dozen, we tested the best candidates on two flat-foam aerobats. The photos tell the whole story, from building the wings to flying the airplanes.

Our tests with a Yak foamie changed not only its leading edge (LE), but also increased its wing area and moved the center of lift forward. These side effects partially explain its handling changes. However, moving the center of lift forward (reducing the static margin between the center of gravity (CG) and the center of lift) can't completely explain the handling changes. In particular, reducing the static margin by moving the CG aft cannot reduce wing rock. And no such side effects affected our blue-foam biplane, because it swapped LEs without changing the wing area or moving the center of lift.

Why serrations work

On most model airplanes, a flat-plate wing has little drag when flying approximately level. Air flows relatively smoothly past the airfoil. Pull the nose up just past the stall angle, however, and the airflow above the airfoil detaches to form large eddies. This suddenly increases drag and reduces lift. A thin airfoil, flying fast, has a sharp stall that quickly eats up both forward momentum and altitude. Other airfoils, such as the thick ones used on slow trainers, stall mildly. At slow speeds, a flat plate stalls at about 8°; a conventional airfoil doesn't stall until 15° or 30°. Wing sweep increases the stall angle even more.

If you have enough thrust to keep increasing the AoA into harrier flight, lift slowly builds up again. Once the nose reaches 45°, lift may even reach its pre-stall value. But drag keeps increasing, of course.

As you pitch the wing up past 45° to a full hover, lift decreases smoothly to zero, and drag reaches its maximum. You see this when, from level flight, you yank into a wall maneuver: moving horizontally with the nose straight up, you bleed off speed very quickly.

The tricky part of this progression from cruise to hover is the sudden loss of lift just after the stall. If only lift would change more smoothly as the airfoil is pitched up. Well, small-scale turbulence at the very front of the wing causes exactly that. It flattens the lift peak just before the stall, and fills in the valley after the stall. This means you don't play the throttle and elevator so much as you move between cruise, stall, and harrier.

Try giving some bite to your next flat-foam ship. It'll only *look* harder to fly. Does it get any better than that?

I must thank John Brandt, Rob Deters, Melissa Goudeseune, Paul Gush, Michael Selig, Juhan Sonin, and Kian Tehrani. Their expertise in various fields was essential to achieving these results.

FIG. 1. I built a dozen balsa LEs that were hardened with laminating epoxy just like you'd harden a smaller balsa part with cyanoacrylate. I pigmented the epoxy so that I could see that it wasn't too thick or thin anywhere.

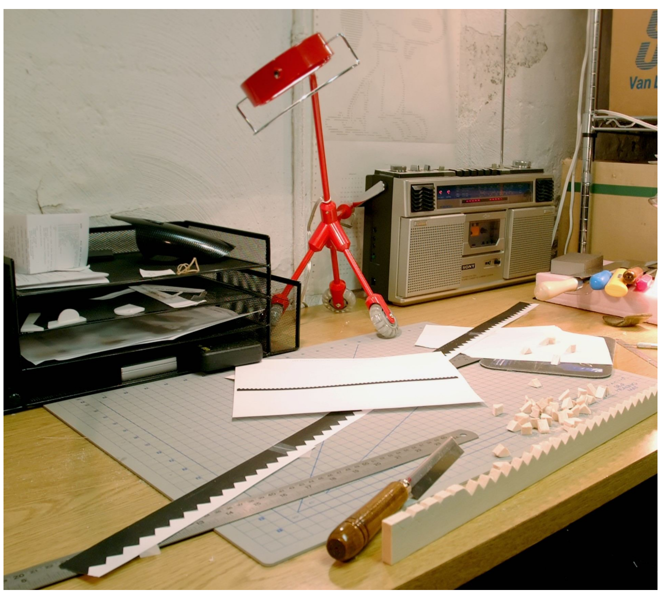

FIG. 2. I designed each layout in Photoshop and printed it out. (In hindsight, I could have transferred the printout directly to the balsa by dampening the balsa with acetone and then pressing the two together for a few seconds.) All of the LEs had the same area, so the wind tunnel tests would be comparable. Photoshop's pixel count tool verified the area of each design.

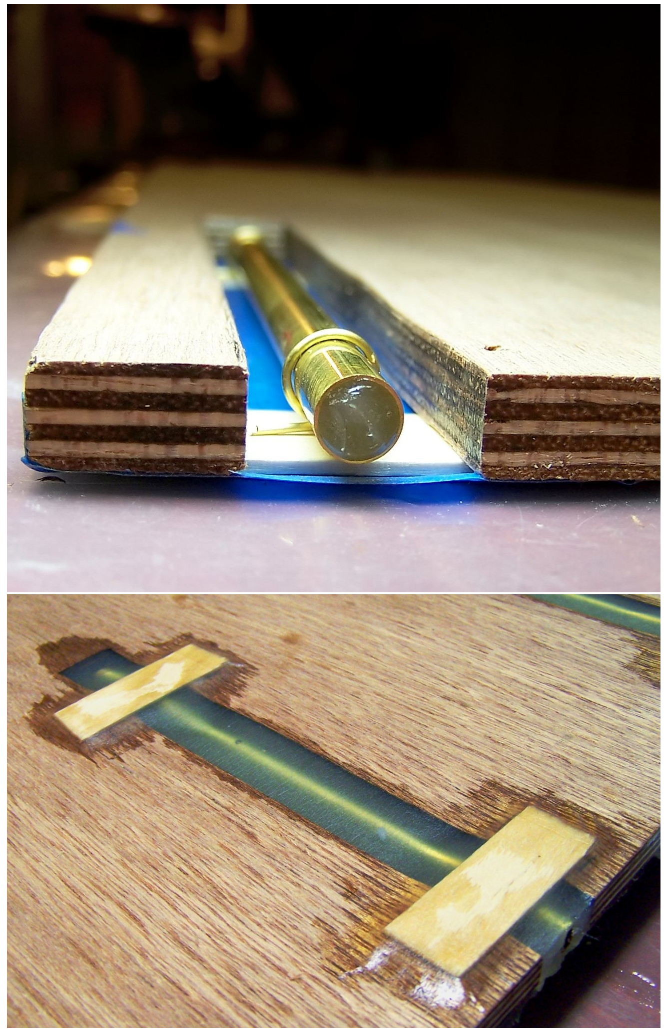

FIG. 3. The LEs would get taped to a solid marine-grade plywood wing. Into the wing, we epoxied four brass-tube pivots. We packed each tube's outer end with petroleum jelly to keep epoxy out. Unfortunately, the curing epoxy around one tube got so hot that the trapped air expanded and slowly blew the jelly out. We discovered this only after the epoxy had hardened, so then we scraped out the epoxy that had leaked in. We carefully avoided denting the tubes, because friction or slop would add noise to the wind tunnel measurements.

FIG. 4. To stiffen the wing and prevent warps, we vacuum bagged it with 6 oz fiberglass cloth. Then, we filled the weave with two coats of Clear Penetrating Epoxy Sealer. Like spackle, this sealer is weaker than the cloth, so the surface became quite smooth after sanding. Even so, the sensitive wind tunnel detected lift at 0° AoA: The slightly rougher face slowed down the airflow, increasing pressure on that side.

FIG. 5. We finally smoothed the wing by covering it with heat-shrink film. It spanned 33⅝ in. and was ⅜ in. thick, to precise tolerances. As shown here with the straight LE attached, its chord was 12 in. As with the other LEs, its average chord was also exactly 12 in., so as a percentage, it was ⅜ / 12 = 3.1% thick. This approximated the wing thickness of the Yak and biplane. Because these had larger chords at the root than the tip, strictly speaking, they had variable thickness: 2% to 2.5% for the Yak, and 3% to 6% for the biplane.

FIG. 6. You can't fit a wind tunnel this accurate into your basement, or into your budget: all the equipment totals a few million dollars.

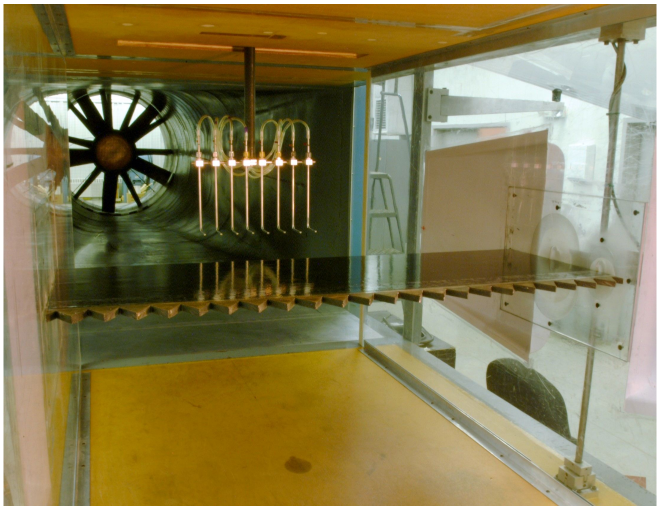

FIG. 7. We then mounted the wing in the wind tunnel. To compute drag, the array of pitot tubes behind the wing measured how much the airflow slowed down. The pitot tubes moved vertically to measure the thick low-speed drag wake. Another sensor outside the tunnel measured the wing's lift. A computer-controlled motor set the wing's AoA for each lift-and-drag measurement. Many more photos and details about the wind tunnel are included in the July 2005 issue of Quiet Flyer.

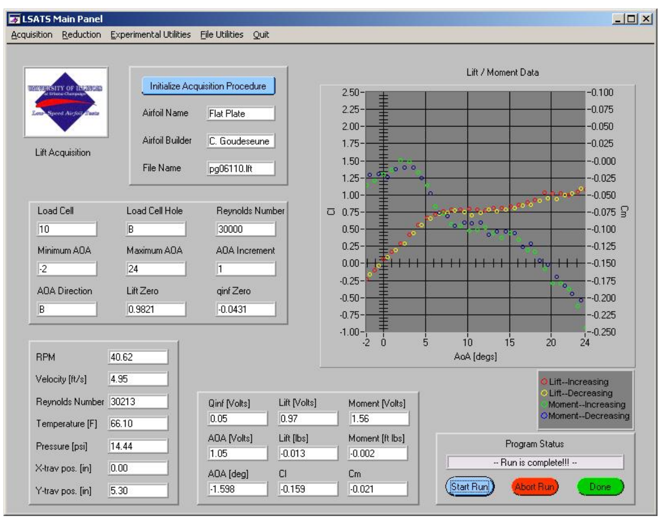

FIG. 8. Here's what the wind tunnel operator sees on screen when running a test. This is the unmodified flat plate airfoil, at a Reynolds number (Re) of 30,000. On the graph, the yellow circles show the coefficient of lift (C_L) as the AoA steps 1° at a time from –2° to 24°. The red circles show the same thing as the airfoil pitches back down. The vertical discrepancy between yellow and red shows how noisy the data are. These data are pretty clean for an airspeed of only 3.33 ft/s. The corner at AoA = 9° is where the stall occurs.

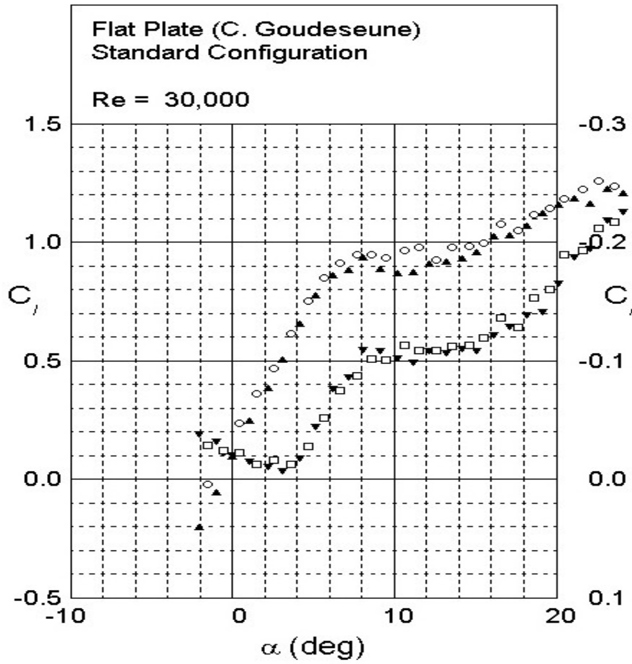

FIG. 9. This preliminary data plot more clearly shows the unmodified flat plate's stall behavior at Re = 30,000. Circles and upward-pointing triangles, like the yellow and red circles on the operator's screen, indicate the coefficient of lift. The final data will be published in Volume 5 of UIUC LSAT airfoil data (see references). The differences between the preliminary and final data are too small to affect the conclusions drawn here, though.

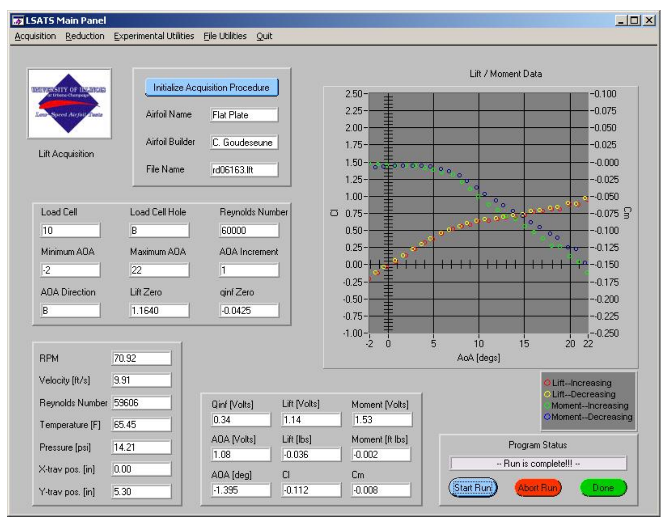

FIG. 10. After about a hundred hours of testing, we found that the LE with steeply pitched, closely spaced triangular teeth had the smoothest increase of lift as a function of AoA, so we chose this one for test flights. The corner at 9° was hardly visible. This plot is for Re = 60,000. Plots from 30,000 to 120,000 look similar. This Re range corresponds to foamie flight from a slow walk to about 15 mph. (60,000 is the lowest Re routinely measurable at Illinois, though most wind tunnels can't get anywhere near this low. A tunnel's lowest Re comes from mechanical hysteresis, slop, and binding in the wing mount.)

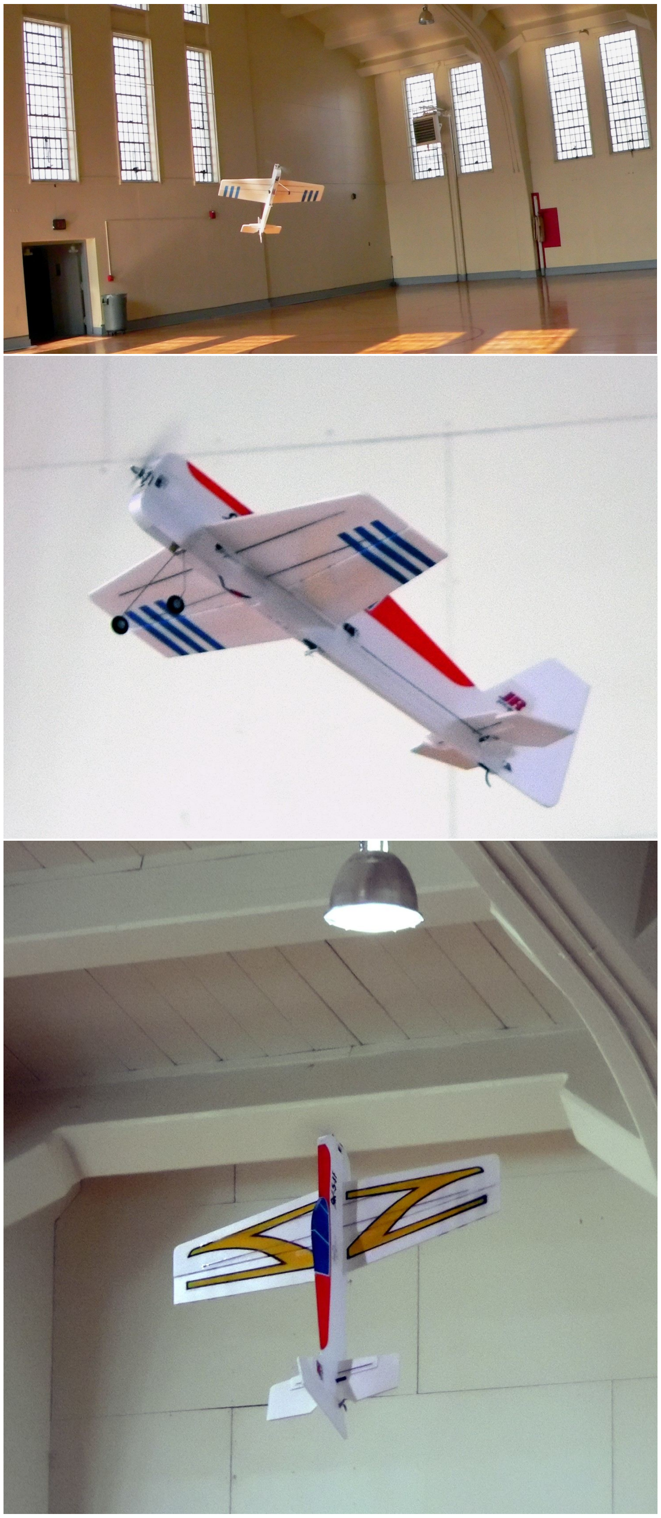

FIG. 11. Lab results won't convince Joe Modeler, so we took our design to an indoor flying arena. John Adams, Horizon Hobby's Engineering Manager, graciously agreed to test fly. First, he flew his E-flite Yak 54F for a few minutes to get the feel of the airplane fresh in his fingers. Like many airplanes of this kind, the Yak suffers some wing rock in a 30° harrier. But in a deep harrier or hover, it is quite stable.

FIG. 12. After John landed, we taped on deeply serrated LEs made of 6 mm Depron. They fit flush to the existing wing, and added no camber (chordwise bend). For our first tests, we mounted them inboard.

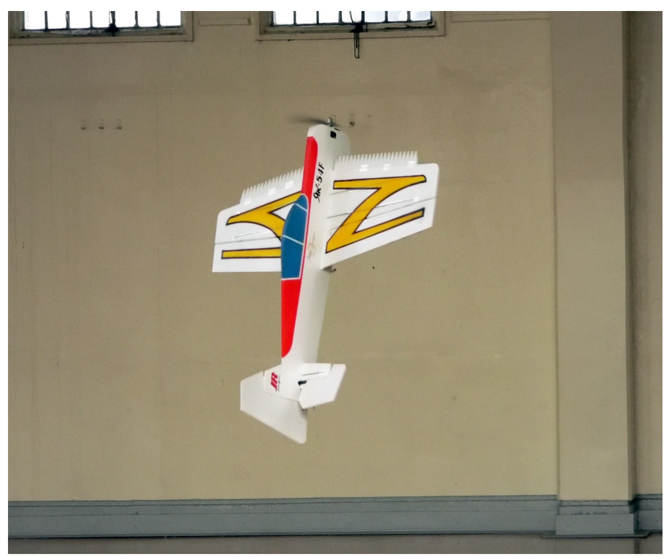

FIG. 13. With the serrations, hovers were as stable as ever. In a harrier, John happily found that wing rock became smaller and slower. The slowdown, in particular, made it easier to keep the wing level, or to maintain a steady roll rate in a rolling harrier. Snap rolls also slowed down. Because one wing stalls in a snap, smoothing over the stall break with LE serrations reduced how suddenly the stalled wing falls.

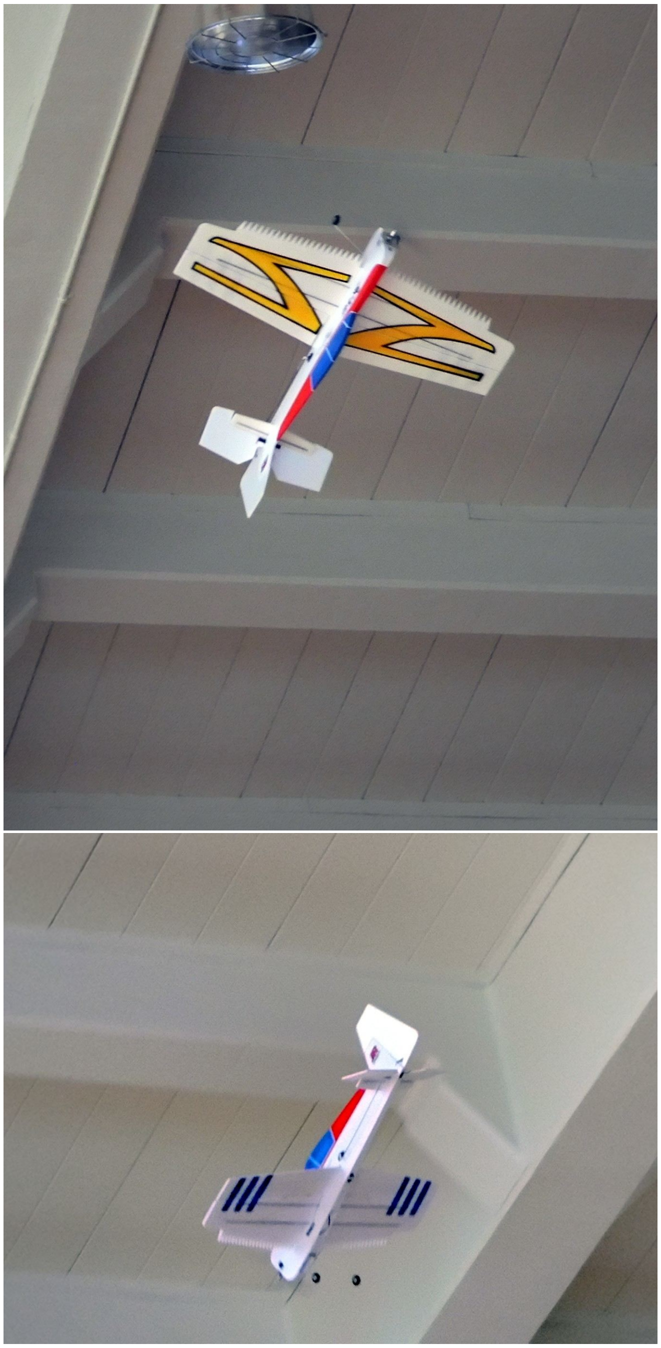

FIG. 14. Inside loops, started from a hover near the ceiling, tightened visibly. A tight loop's rapid pitching normally detaches airflow from the wing's upper surface. But the serrations kept the airflow more attached, producing more lift—in a loop, more "centripetal force." (The serrations also encourage the vortices that appear at the LE and flow aft in unsteady airflow. Energy may be stolen from the rapid pitching's spanwise vortex and given to the friendly chordwise vortices. This so-called dynamic stall again increases the deeply stalled airfoil's lift.) Also, the smoother airflow past the elevator would increase its effectiveness. Outside loops from hover, also called waterfalls, became twice as tight. This extra tightness may be because the elevator's strong downward deflection reduced interference from the rudder.

FIG. 15. When we removed the serrations, John confirmed that the Yak's original behaviors returned. Next, we reattached them to the wing, but outboard this time. The Yak behaved much like it did with them inboard. Loops didn't tighten quite as much, perhaps because the serration-smoothed airflow was outboard of the elevator.

FIG. 16. In flight, the serrations were barely visible, because the tooth-to-tooth gap wasn't much more than the wing's thickness. Also, John was having too much fun yanking around his improved Yak to hold it steady for the camera! He later added serrations to a few more airplanes, and said he got similar results.

FIG. 17. Because indoor test results won't convince Joe Outdoorsman either, I built a heavy blue-foam biplane that could tolerate wind for outdoor tests. With a straight LE, it had a nasty tip stall. As with the Yak, serrated LEs slowed the tip stalls of this model down greatly. Both shallow and deep harriers became comfortably stable. Transitions between level flight, harriers, and hovering were much smoother. (Elevator throw looked small in harriers, because I mixed elevator to flaps to increase pitch authority.)

FIG. 18. I mounted LEDs on the wingtips, the struts, and the rudder. They helped me to orient the biplane in dim light, as Illinois winter days are rarely calm and bright. Though the maiden flight was at night, actual flight tests were conducted during the late afternoon, with winds under 5 mph and temperatures just above freezing. To avoid overloading the speed controller's 5 volt supply, the LEDs drew power directly from the battery. Thus, when they got dim, I knew it was time to land.

FIG. 19. When pitching up rapidly, cassette-tape streamers revealed the separated airflow above the wings. Flow above the lower wing was smoother, probably flattened out from high pressure under the upper wing.

References

Horizon Hobby
4105 Fieldstone Rd.
Champaign, IL 61822
Phone: 800-338-4639
Fax: 217-355-1552
Web Site: horizonhobby.com
Horizon sells the E-flite™ Yak 54F 3D ARF for $59.99.

Prof. Michael S. Selig and the University of Illinois at Urbana-Champaign (UIUC) Low Speed Airfoil Tests (LSAT) Program
Dept. of Aerospace Engineering
University of Illinois at Urbana-Champaign
104 S Wright St.
Urbana, IL 61801-2935
Web Site: https://m-selig.ae.illinois.edu/
E-mail: m-selig@illinois.edu

SoarTech Aero Publications
Herk Stokely
1504 N Horseshoe Circle
Virginia Beach, VA 23451
Web Site: https://m-selig.ae.illinois.edu/uiuc_lsat.html
E-mail: soartec@aol.com
Publisher of books and CD-ROMs for the UIUC's LSAT. The book *SoarTech 8* includes lift and drag plots for a conventional flat-plate airfoil at low Reynolds numbers.

Acknowledgement

This article was first published in Quiet Flyer Magazine, April 2006, pages 18–23. Kiona Publishing graciously granted permission to republish.

FIG. 20. Serrations didn't slow down the biplane's snaps, perhaps due to enormous control throws, a small wingspan, and tapered wings. (Short, tapered wings increase the roll rate, much like a pirouetting skater speeds up when she folds her arms.) For large throws, I mounted the aileron servos directly on the hinge line: linkages can never increase throw. To avoid stripping gears in a rough landing, I used metal-gear servos.

FIG. 21. The biplane differed strongly from the 12 oz Yak floater, proving the serrations' effect for a range of airplanes. It weighed 15.5 oz, but spanned only 28 in. The wing area was 157 sq in., so the wing loading was a hefty 14 oz/sq ft. The CG was a moderate 30% of the mean aerodynamic chord. Up front, an 11.1 V lithium polymer battery powered an Ultrafly™ C/13/24H brushless motor geared 3:1. With an APC 10×5 propeller, this produced 17 oz of thrust at 70 W, just enough to hover.