# ELIPPSE™ Propeller



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**Paul Lipps spent many years in the aerospace industry, 28 of which were with GE on the ATLAS Space Launch Vehicle radar/computer guidance system at Vandenberg AFB. While with GE, Paul developed high accuracy refraction-correction equations and a tropospheric radar noise-model for use in the Kalman-filter guidance equations. He also designed a computer-driven radar simulator which phase and amplitude modulated X-band signals, which were injected into the radar's antennas to produce a high-fidelity, interactive radar simulation of an ATLAS flight. This allowed radar checkout, training of radar and computer operators, simulation of radar and computer problems, and gave accurate ATLAS flight simulation for checkout of the computer guidance program under non-nominal trajectory, booster performance, as well as high tropospheric-noise conditions.**

**Prior to these accomplishments, Paul worked for Bell Telephone for 6 years, and then spent 5 years working for Burroughs Corp. on the guidance computer for the ATLAS D ICBM at Vandenberg AFB.**

**Since his retirement, Paul has developed equations and the computer program for the design of high efficiency propellers. In addition to this, Paul has worked with Klaus Savier of LightSpeed Engineering in the design of the PLASMA series of electronic ignitions and is now working on an electronic fuel injection system.**

**Paul's flying passion came to life when he was 17, while he worked at a seaplane base in his native town of Pittsburgh PA. Although at the time he built 14 hours on floats, his flying had to take a back seat to life. Some time was spent with a J3 flying club, but it wasn't until 1989 that Paul received his PPL in a C-172. He has since built over 600 hours SEL, with 400 of that being in his (and another's) Lancair 235.**

**Paul has been a strong supporter of *CONTACT!* since he was first introduced to us a little over a year ago. We greatly appreciate his support, and look forward to publishing his future contributions. *~ Pat***

## *THE PROGRAM*

Several years ago I loaded Peter Talbot's "Prop Performance" Basic program in my computer. I obtained this program from a listing in the book "Modern Propeller and Duct Design" by Hollman and Bettosini. After playing around with the program for a while, I used it as the basis for developing a program of my own. I read about propeller, wing, and airfoil theory in several books, and tried to incorporate what I had read into my program, things that were not contained in the original program. Things like the effects on lift and drag coefficients from Reynolds number and high Mach compressibility. Things like lift distribution, design lift coefficient, as well as planform.

## *THE PROPELLER IS A WING*

It's stated in all books on wing theory that the most efficient wing makes use of an elliptical planform/elliptical lift distribution. Since a propeller is basically a wing in rotary motion, creating its lift and thrust from the combination of rotary and forward motion, I reasoned that an elliptical lift would be my "E" ticket choice.

Lift on a wing is a function of the flow of air generating a force which is resolved into lift and drag. That force is proportional to the square of the velocity. Double the speed and the available lift goes up by four. Cut the speed in half, and the available lift is only one-fourth as much.

All parts of the wing of an airplane basically go through the air at the same airspeed, except in a tight turn at low airspeed. But now consider that on a propeller, the rotational velocity at any point on it is mainly based on the radius at that point. Except for propeller-induced inflow, the static flow of a 72" rotating propeller will be six times as fast at the 36" tip as it is at the 6" hub/spinner radius. This means that the available force at 36" will be 36 times as great as at 6"! A propeller having a constant chord, with correct helical twist, would be similar to having a wing on a plane that had a tip chord 36 times wider than at the root! This would be exactly the opposite of an elliptically-loaded wing. Think of the incredible bending force that would result from a wing like that.

To obtain a propeller with an elliptical lift distribution, it is first necessary to start off with a planform that has a constant lift distribution, then modify this by the coordinates of an ellipse. Without considering forward speed, a constant lift planform would result from tapering the prop inversely proportional to the radius-squared, making it extremely wide at the root, very narrow at the tip. See the propellers on the Carter-Copter and AeroVironment's 14-motor solar-powered flying wing.



**Paul's propeller is like none other, seemingly breaking all the "rules", yet the performance is unparalleled.**

A wing has to operate over a wide range of speeds, in some cases as much as 5:1; 3:1 is not at all unusual. That means the available lift force will vary over a 9:1 to 25:1 ratio. At the lower end, near stall, the wing will operate near the peak lift coefficient. For a wing with flaps, that would be about 2.0. At high speed, the $C_L$ would only be one-ninth as much, or 0.22. A propeller, on the other hand, does not have nearly as much velocity variation along its span, except in the root area, since its major velocity is due to rotation, so it does not need as much $C_L$ range. This is a real advantage, as it is possible to make use of the higher lift/drag ratio of a more highly-loaded airfoil. Some of the laminar-flow airfoils in the 63-65 series have L/D ratios in excess of 100 at high $C_L$.

### *AIRFOILS*

A laminar flow airfoil will have a minimum drag coefficient, $C_D$, of about .004. On a symmetrical section, that minimum occurs at $C_L = 0$. Dividing the $C_L$ by $C_D$ gives a zero lift/drag ratio. Not something to write home about. But taking that same section and giving it sufficient camber so that this $C_D$ minimum occurs at a $C_L$ of 0.55 would yield an L/D of 110 to 138!

A symmetrical airfoil must operate at a high angle-of-attack in order to generate lift, so it also has a high induced drag, which results from the rearward tilt of the airfoil. A cambered section can generate a moderate $C_L$ at zero A-O-A, so has minimum induced drag. Did you ever look at the where the bugs are smashed on the leading edge of your wing? Notice that they are usually just *above* the leading edge. That is because you usually pick them up when landing over a field which is next to a runway and you have the flaps down. With the flaps down, the airfoil is very highly cambered and generates lift at a *negative* A-O-A; the bugs hit on the top of the airfoil, not the bottom!

Most of the wood propellers you will see generally have a flat-bottom airfoil that is somewhat similar to a Clark or RAF section. These are referred to as turbulent flow sections. Two of the big name prop makers I'm aware of use a section which has a totally-flat bottom with a sharp leading-edge! A sharp leading edge will only perform somewhat well when it intercepts the incoming flow on a line that bisects the edge angle, i.e. where the chord is parallel to the relative wind. At small flow angles off this line the flow will get tripped right at the leading edge creating much drag. How many subsonic jets have you seen with a flat-bottom airfoil? None, right? Those airfoils have drag coefficients almost 50% greater than the laminar flow airfoils. For that matter, when have you seen a high performance sailplane with a flat-bottom airfoil? Does this give you a clue as to proper airfoil selection and use? Granted, laminar flow sections are harder to carve, but well worth the extra time it takes to make them. Why use high-drag airfoils on the high velocity of a prop? As long as the Reynolds number is greater than about 400,000 the laminar flow section will outperform the turbulent flow sections

### *BLADE ANGLE*

Now it is necessary to determine the blade angle verses the radius, the helical path each portion of the blade follows as it passes through the air. Without consideration of the A-O-A, the tangent of the helical path at any radius is simply obtained by dividing the design forward speed by the rotational velocity at that radius. For a plane with a design speed of 200 mph, we multiply by 22/15 to get the speed in ft./sec. To get the rotational velocity at a given radius, we multiply the radius, in inches, by 2 X p X RPM/60 X radius/12. With the engine operated at its rated 2800 rpm, we would obtain 63.4º at 6" radius, 36.9º at 15", and 21.8º at 30".

Some would look at that high angle at 6" radius and have a tizzy! The inner portion of a prop generates no thrust, right? WRONG! The portion right up to the spinner can generate very high thrust-to-horsepower ratios.

But you'll say "Look how steep the prop is here. It's working against the engine." Well, trigonometry to the rescue. We can resolve the lift force at any radius of the blade into a forward thrust force and a rotary force acting against the engine's rotation. Using the root and tip angles we just obtained, one unit of lift at 6" would give 0.45 units of thrust and 0.89 units of rotary force. One unit of lift at 30" would give 0.93 units of thrust and 0.37 units of rotary force. But! Now we have to multiply the rotary force by the radius, in feet, to get the torque force acting against the engine. That means that the thrust/torque ratio at 6" is 0.45/(6"/12" X 0.89) = 1.00, and at 30" is 0.93/(30"/12" X 0.37) = 1.00.

The root section can do one of three things: generate thrust as well as drag, generate no thrust as well as drag, and generate reverse thrust as well as drag. The drag is always there; only thrust can be designed-in!

### *COWLING AND INLETS*

If the prop has too little angle in the root region, it develops reverse thrust, slowing down the air needed for cooling. That is why so many cowlings have their cooling inlets mounted so far outboard, where the prop's angles are more conducive to producing thrust. My inlets are mounted with their inner wall in line with the spinner. So too my induction inlet. In this way I pick up the accelerated flow displaced by the spinner. My O-235, with 123 hp., gets its cooling air from 1.5" by 4" inlets, 6 in² per side! Compare that to others! And guess what! My engine runs too cool; I can't always get the CHT up to the correct temperature of 385°F/195°C!



**Many aircraft manufacturers design their cowls with the inlets as far outboard as possible. This is due to the normally stagnant or even negative air flow near the spinner. Paul's propeller design is such that the propeller is producing thrust at the root, allowing the cooling inlets to be inboard.**



**This end view of Paul's propeller shows the high angle of incidence at the root, and the extremely thin, low drag tip.**

### *ANOTHER MYTH*

Many propeller articles state that there is increased drag from having the prop accelerate the air over the cowl. In other words, if the prop is producing thrust there, the cowl will have more drag. So by having the prop not produce thrust, there will be no additional drag. Following this line of reasoning, it would seem to be better to have a lot of reverse thrust in front of the cowl and so reduce its drag! Wow! That really makes sense! Why not just use a pusher prop on a tractor airplane so that there will be no air flowing to the rear over the fuselage and so no drag? The air being sucked in by the prop from rear to front flowing over the fuselage will propel the plane forward?

### *THE TRUTH*

My prop in cruise at 200 mph gives a delta V to the air behind the prop of less than 10 ft/sec, even less in the inner six inches. 200 mph is 293 ft/sec. (293 + 10)/293 = +3.4% increase in the air speed over the cowl. Not too much cowling drag created here.

A school of propeller theory says that the cowling behind the propeller causes a large bubble of air to be pushed ahead which causes a slowing of the flow into the prop. With this supposed slower flow-field, it would be necessary to take this into account when calculating the helix angle which would result in reduced angles. I think much of this theory is from the '30s when planes had radial engines with large surface areas normal to the airflow. I've even seen illustrations showing the view looking downward on the front of the cowl/prop which shows the cheeks of the cowl sticking out each side apparently blocking the airflow. But when the cowling is viewed from the side, it can be seen that the line from the spinner usually blends in smoothly to the top and bottom of the cowling. Only that portion of the cowling around the inlets is normal to the flow, and if the inlet apertures are properly sized, there is little reverse flow. But consider; if the

prop angles are reduced in this area, when they pass through the top and bottom region unblocked by the cowling, they will be at too low an AOA, producing either no or reverse thrust there. Only in the small region where the flow velocity is somewhat reduced will the prop be producing thrust. With the correct helix angles, the prop will be at the correct AOA through most of its revolution (especially the 180$^{o}$ arc over the top of the cowl, as viewed from the front), and at a higher AOA in the blocked area, but still producing thrust!



**We first met Paul at the 2003 Golden West Fly-in, Marysville CA. We were looking for interesting aircraft to showcase in *CONTACT!* Magazine. We found Paul in line with a several other planes, awaiting the end of the air show so that they could leave.**

### *THE TIP*

This brings up another issue. It is easy to see that a drag force acting near the tip can generate large values of torque due to the long lever arm. A Cessna 182 flying at 7500', 2700 rpm, 156 mph, on a standard temperature day, with a 72" prop, will have a tip Mach of 0.81. Its drag coefficient will be at least three times as much as in the root area, that is, if the tip is in good, smooth condition without a lot of pitting from stones and rain. But on a propeller, as on a wing, there is no lift at the tip. The lift pressure differential on a wing or prop goes to zero at the tip, therefore, no lift. But there is drag, and lots of it due to the high Mach. And since area is a product of span and chord, the wider the tip chord, the greater the area, the greater the drag. This is one of the main reasons why props with wide, rounded tips, are so inefficient. A high efficiency prop will have a pointed tip, zero chord. The high-Mach, wide, rounded-tip props are also the ones that generate so much noise. That noise is engine power being thrown away. And any prop that further complicates a wide tip with a wide, turned-under or turned-up tip really throws away engine power. Those may look very techie, but they aren't very efficient!

### *ANOTHER PROPELLER*

The following will illustrate how important to efficiency it is to have the root section of the prop produce thrust and to minimize tip drag. We had a prop with turned-under tips, absolutely flat bottom, sharp leading edge, and a root angle about 15° less than the correct helix angle. This prop gave 214 mph TAS at 8000' D.Alt. and 2950 rpm. Removing the turned-under portion of the tips and creating a "slashed" tip, along with adding fiberglass layers from the spinner out 12" to increase chord 1" and increase its angle, gave a prop that gave 218 mph TAS at 8000' D.Alt. and 2720 rpm. By a method to be shown later, the efficiency of the prop was increased by 15%! More speed at less power!

A slashed tip on a square-tip prop is created by first drawing a line across the blade on the bottom surface about 15% of the tip chord in from the tip. Shape the tip from this line straight radially-outward up to the top surface of the tip, forming a very sharp edge. This sharp edge trips the vortex at the very outer edge, giving the most efficient tip. It will increase full-throttle rpm by 20-50, and give 1-5 mph speed increase.

### *PRACTICAL APPLICATION*

The first prop I designed (with my prop design program) was for use on a Lancair 235 with an O-320. It was to be used for mild racing and was to be able to turn 10% over red-line rpm. It was made of carbon fiber over a laminated wood core. The wood core was carved on a CNC machine, especially made for propeller carving. When I gave the chord and angle data to my friend who makes props, he wanted to know if I really wanted him to make it for me as its chord and angle distribution was like nothing else he had ever seen. He and others felt that it would not work well, if at all.

I can tell you I had a lot of trepidation at this point, not only from the comments of those I respected, but also because the prop really did have an extremely unusual planform and helix angle distribution. One of my programs predicted the Lancair's speed at 1000', 5500' and 10,000' density altitudes, at 100 rpm increments from 2400 rpm to 3100 rpm. Since this was my first go at prop design, I would have been happy if it performed within 5%-10% of my predictions. The prop met or slightly ex-

ceeded the speeds at all test points. We were able to get 2000 ft/min rate of climb at 110 mph IAS, 2700 rpm, and 240 mph at 5500' D.Alt. at 3150 rpm.

The program predicted the peak cruise efficiency at 90%. Some other props which we tested on the Lancair ranged from 12% to 27% less efficient than this prop. The 27% figure was relative to that flat-bottom, turned-under tip prop that I later modified! That's like throwing away 19 hp to 43 hp on a 160 hp engine.

My latest prop is a 63" diameter three-blade for my Lancair 235 with an O-235 L2C. It is fiberglass over a laminated wood core and made by Craig Catto of Catto Props. It uses a 13% thick, 63 series laminar flow airfoil. The blades have a lot of flex near the tip, and can be bent forward about 1" without too much effort. It should be remembered, though, that there is little lift/thrust near the tip, and combining that with the centrifugal-stiffening, this flex usually occurs only in static conditions, and not in cruise.

I designed it to give 200 mph TAS at 10,000' density altitude at 2800 rpm. I am actually getting about 202-203 mph. With me and 20 gallons of fuel for 1350 lb gross, I get 1550 ft/min ROC at 2370 rpm, 110 mph IAS, at sea-level density. That computes out to about 82%-84% efficiency in a climb! That's better than most fixed pitch props get in cruise! On a recent trip with a friend, the plane had 211 mph TAS at 8330' density altitude at 2840 rpm, 6.8-7.0 gph! Several people I have spoken with that have Lancairs with an O-235 tell me they get more like 180 mph-200 mph.

### *EFFICENCY CAN MEAN ECONOMY*

On May 17th, 2004, to see what fuel economy I could get by slowing the plane down, I got a fuel flow of 2.8-3.3 gph at 130k TAS, 150 mph. That's 45-54 mpg! As a point of comparison, I had a Great American 62" diameter prop which I tried. At 8042' D.Alt., I got 202 mph TAS at 2950 rpm, 7.9 gph.

To get a full-throttle efficiency comparison between two propellers operated on the same plane at about the same D.Alt., multiply Prop2 rpm times Prop1 $TAS^3$ then divide by Prop1 rpm times Prop2 $TAS^3$. So 2950 RPM X $(211\ TAS)^3$ / 2840 RPM X $(202\ TAS)^3$ = 1.18, that is, 18% more efficient.

### *SINGLE BLADE MYTH*

One of the myths that has been propagated in the aviation community, to the point that it is "gospel", is that the most efficient prop is a single blade; all higher number of blades falling further and further short of this paragon. Did you ever consider that a single-blade prop, developing thrust on only one side of the plane as it revolves, would cause the engine to cone violently in its mounts as it is twisted by the prop? The European's latest turbo-prop transport, the A400-M, has ***eight-blade props***! The Boeing MD-900 helicopter has a five-blade rotor. A popular regional turbo-prop airliner has a five-blade prop. Hasn't anybody filled these plane-makers in on the errors of their ways? In a recent edition of Kitplanes, the author of an article on props uttered the same fallacy. He maintained that multiple blades interfere with each other. When I pointed out to him that at 200 mph and 2800 rpm, the blades on my three-blade prop follow three distinct helical paths through the air, and each blade is 25" ahead of the previous blade at the same point of rotation, he rather lamely explained that in static conditions interference occurs. STATIC? Who uses static thrust? Airplanes are meant to fly, not pull tree-stumps!

### *STATIC AND AERODYNAMIC BALANCE*

Another thing to consider about props is balance. Whenever someone speaks of balancing a prop, they are always referring to mass balance. But just as with the case of the single-blade prop, if any one blade or a combination of more than one pull harder than the others, there will be a thrust unbalance that will cause the engine to cone in its mounts. This effect is exactly the same as the effect from a mass unbalance. In a mass unbalance, the mass center of the blades is not coincident with the crankshaft rotational center; this causes the engine-propeller system to rotate about its common mass center, generating a whirling or coning on its mounts. With an aerodynamic unbalance, due to blade-to-blade differences in chord or angle distribution, the thrust center does not coincide with the rotational center. The result? Engine whirl! This can also result from the plane of the prop hub face not being equidistant from all of the blade angles. To illustrate, consider what would happen if you placed a shim between the hub and crankshaft flange on the side of a two-blade prop hub 90º from a line between the two blades. That would cause one blade to be at an overall lower angle, and one to be at a higher angle.

I had a prop that I balanced over and over and it still shook the plane. When I took a piece of paper and drew an outline around each blade and compared them, it immediately became apparent that one blade had about 1/4" more chord than the other over a short span. After correcting this, the prop was very smooth. I have found that a prop could actually have a slight unbalance and you would never detect it over a four-cylinder engine's own roughness.

### *PITCH– THE "P" WORD*

You'll notice I never once used the word "pitch" in reference to my propeller. In my opinion, that word should be reserved for use with screws and worm gears that travel a definite linear distance per revolution. In order to discuss a propeller using "pitch", it's necessary to introduce another word - slippage! Here again, I feel that slippage should only be used to describe a condition in which a device that is supposed to have a 1:1 relation between input and output does not, such as a v-belt or clutch. Since a propeller is nothing more than a wing in rotation, if pitch and slippage are appropriate for a propeller, then they should also be appropriate for a wing. Which they're

not! Nowhere have I seen these terms applied to the main and tail rotors of a helicopter, or the rotor of an autogyro. Why? Aren't they also propellers. In a hover, the helicopter's main and tail rotors must have 100% slip, since they go nowhere. See what I mean?

It is really an inappropriate, non-technical term for use with props, and introduces the idea that all propellers of a certain diameter and pitch are alike. It's as if chord and planform have no bearing on a propeller's characteristics; but nothing could be further from the truth! Go buy the same diameter and pitch prop from three different prop-makers and you'll get three different performances. That is the source of much frustration for someone shopping for a prop for his plane. To properly characterize a prop, the prop-maker should tell you the engine horsepower required to turn the prop at a given rpm, density altitude, and speed, as well as the efficiency under those conditions. I'd like to see you get that information from any of them!



**Just in case you think we are pulling your leg with this propeller design, here's photographic proof that it actually works! The camera's shutter didn't completely stop the prop, but you can still make out the planform of Paul's 3 blade prop, as he departs the Hanford (HJO) airport.**

I would like to design propellers for various and sundry aircraft, but in order for me to design a prop for a plane, I have to be able to form a drag model of the plane for my equations. The best way to do this is to have one of my props installed on a plane and then measure the plane's performance with it. So far I only have the two props, and the 2-blade is on loan for a race plane for Reno. I can form a less-accurate model by measuring the chord and angle of someone's prop every inch from the spinner to the tip and using that data, along with the full-throttle performance of the plane with that prop to obtain the drag model. This requires the use of a very accurate electronic tach, and flying the plane around a wide circle while measuring GPS-derived ground speed and holding a constant altitude to minimize speed variations. It's also helpful to have a fuel-flow meter in order to determine the actual installed engine horsepower, not the exaggerations of some of the engine-makers! This makes use of the fact that a moderate-compression-ratio four-cycle engine (8:1- 9:1), leaned for best power, will burn about 0.5 lbs./hp-hour. Using this and 5.9 lb./gal., you can estimate the installed horsepower to within about 5%.

By the way, the name ELIPPSE™ as you can see, is a bastardized spelling of the word "ellipse" using my name last name LIPPS. I chose it because it refers to the elliptical lift distribution of my propeller design. My prop's logo (seen on page 8) consists of a 3:1 ellipse surrounding the LIPPS name, with the Greek letter epsilon in front of my name and behind it in reverse ?LIPPS? . Epsilon looks like a squashed, somewhat-triangular letter "C" with a horizontal line in the middle to make it a rounded "E". Epsilon in mathematics is used to refer to the long/short axis ratio of an ellipse, its eccentricity.

There are people writing articles about props that say that the elliptical lift distribution does not work for props, and mention the work of theorists such as Theodorsen, Goldstein, and Betz. But, as they used to say, the proof of the pudding is in the eating! If someone can design a prop for a particular aircraft and predict beforehand its efficiency and its performance to within 1%, well, I'll tell you, that's where you want to put your money!



**From behind, the unusual shape can be clearly seen.**