Inverse Pressure Gradient Matching

. . . and other ideas for designing fast, low wing airplanes that climb and turn like mad

BY MIKE ARNOLD

In 1993, shortly after I set the C1aO record in the AR-5, my friends and I made a video tape ("Why it goes so fast"[1]) in which, among a lot of other things, I explained my reasons for configuring the wing/body interface as I had. I went on for 20 minutes about clues I'd discovered in Hoerner[2] that led me to make the sides of the fuselage parallel, from the thickest part of the airfoil, all the way back to where the trailing edge of the wings intersect the body. Bruce Carmichael[3] and I spoke about the importance of this fuselage shape, and of the expanding radius wing root fairings, in reducing the rapid deceleration of flow over the after part of the wing, at the root. This deceleration leads to drag and separation, especially at high angles of attack. I also noted (after Bruce's visit) that I had sized and placed the canopy in such a way that it filled out the fuselage cross section from a point directly over the thickest part of the wing, all the way back to a point directly over the trailing edge, where the canopy peaks. I said that I thought all this attention to the wing/body intersection, and the position of the canopy relative to it, paid off in an improved rate of climb and smaller turning radius (I wanted a dogfighter), and lower drag at top speed. The AR-5 climbs well, considering its horsepower; it turns inside all the airplanes I've flown it against, and it holds a world speed record4. So, I thought I was really on to something. But, I'm not an engineer. What do I know?

INTERFERENCE, THE NEGLECTED DRAG?

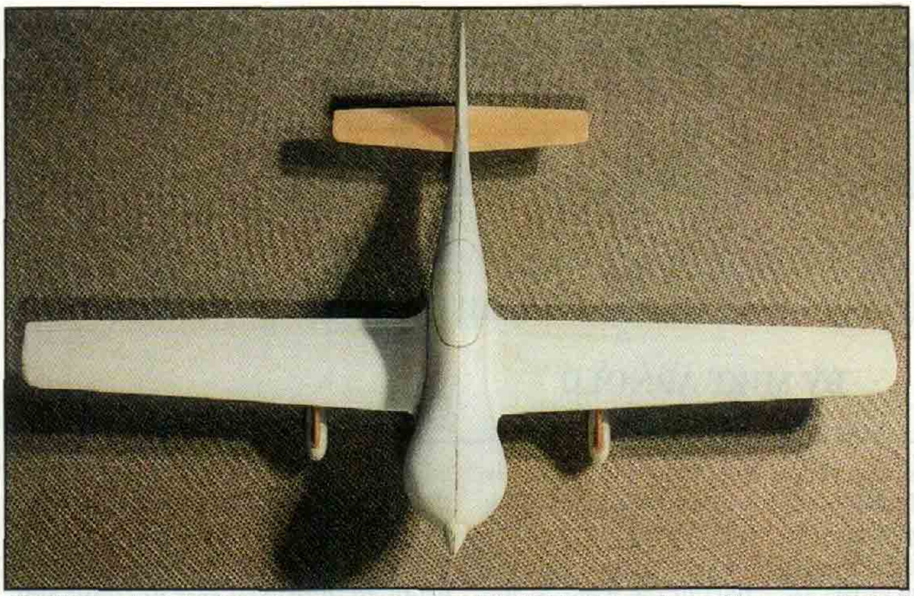
Bruce didn't really have a comment on the importance of incorporating the canopy in the overall wing/body design. He was enthusiastic about the parallel fuselage sides and the expanding-radius wing-root fairings3a, but I think he felt the canopy was too far away from the wing to have much effect on the intersection ("I think pressure drops as the square of the distance from its source." — Bruce Carmichael). So did most of the other eight designers I called. In fact, the general consensus was that I was making too big a deal of interference drag itself, it being such a small percentage of the overall drag of the airplane. But, I'd seen color renderings of pressure distributions over airliners and, even at cruise speeds, I could see that the low pressure fields over the top of the wing went right up the fuselage sides and met at the top. **Something** was definitely going on up there where I wanted to put a canopy, and I couldn't just ignore it.

Airfoil designer and self-proclaimed irascible curmudgeon Harry Riblett[5] thought the canopy stuff was a good idea though, and Irv Culver[6] did, too. I framed my case for Irv in more depth than I had for the others. I talked more about pressure gradients with him, which I hadn't done in the article I wrote for ***Sport Aviation***[7] and had only touched on in the video. I'd had the good fortune to work with Irv briefly on another project, and I knew he had a special interest in interference drag since before his days with Kelly Johnson at the Skunk Works, so his support was very comforting. But I was kind of hoping that everyone else would see the logic in what I was doing, too, and they'd all come right out and say what a great idea it was, and we'd all be designing airplanes that looked vaguely like the AR-5, happily ever after (and I'd be famous, and people would bring me sacks of money, and so on). But it wasn't happening. Three years had gone by and no one was saying anything about it. The videos were sent out and people wrote rave reviews about them, but they rarely mentioned the interference drag stuff. No one else either challenged or confirmed the idea that canopy position was an important ingredient in the wing/body soup, or even that the wing/body drag question itself was important. Two known rebels and I thought it was a good idea, and I was still as broke as ever.

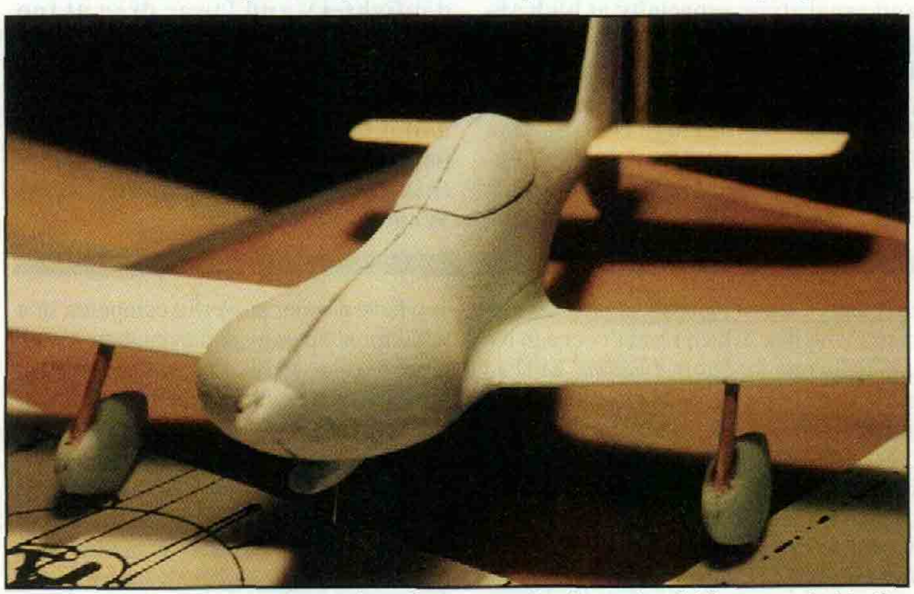
The problem with trying to talk about wing/body interference drag is that it's so hard to measure that kind of drag, unless you have a super powerful computer, or a wind tunnel handy, and even then it's no piece of cake. Most of us will be forced to fall back on a few tried and thought-to-be-true formulas, based on previous estimates that seemed to work, to calculate the interference at the wing root of our designs. Hoerner suggests simply calling the drag of the wing surface covered by the fuselage equal to the wing root interference drag, but many folks just guess about this one. Most of the designers I talked to said that interference drag is generally thought to be (guesstimated to be) 4% to 6% of the total drag of an average airplane, so we're only talking about a couple of miles an hour anyway, so why waste your time? But here's what I saw in Hoerner that makes me think it's important to keep interference drag as low as possible on an already clean design.

THE SUPER MESSERSCHMITT

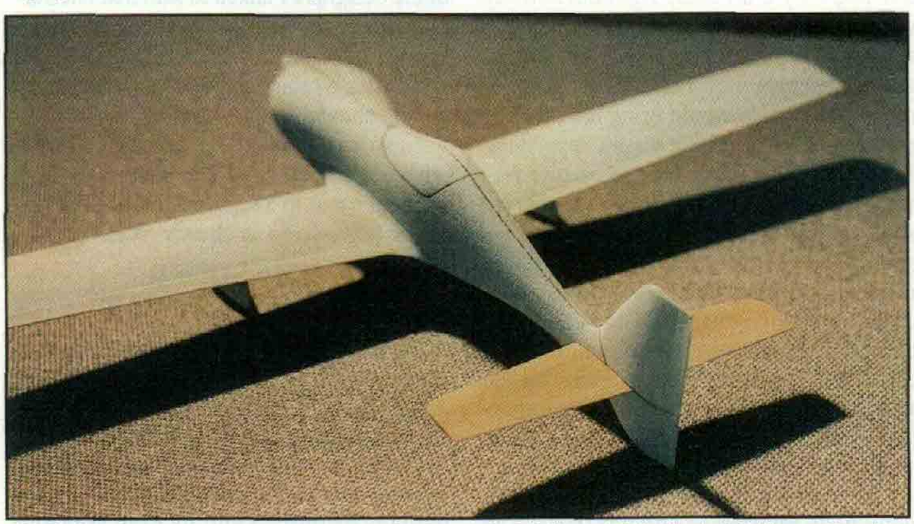
Hoerner did a lot of wind tunnel work in Germany during the war, and in *Fluid Dynamic Drag* he presents some fascinating drag breakdowns of the Me 109, both from calculations, and from experimental data from the tunnel. Each nut and bump and antenna is examined and its drag area and coefficient calculated. It's been very useful



AR-6 Formula 1 design, showing engine cowl fairing in to fuselage sides over point of max. thickness on wing. Fuselage sides are then parallel back to trailing edge.



AR-6 showing sort-of-round cowl, and wing root leading edge fairings needed in the high pressure area created by back of cowl.

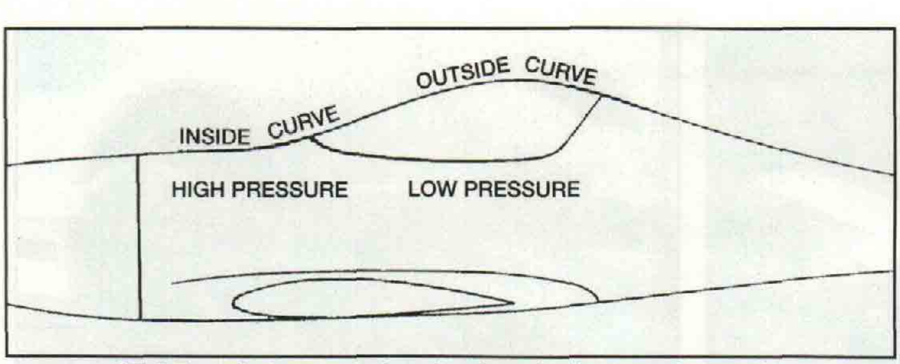


AR-6 showing high pressure area on horizontal stabilizer (aft half of airfoil) meeting low pressure area on vertical stabilizer (around point of maximum thickness on vert. stab.).

for me to see exactly what contributes drag, how much drag, and why. Great stuff. At the end of the chapter he mentions that the speed of the 109 would jump from 378 mph to 396 mph if the same airplane, with the same shape and airfoils, could be made completely smooth . . . no antennas or gun ports or rivets or gaps . . . absolutely smooth. He dropped it there, but it made me think about what that means in terms of the AR-5 and interference drag. The AR-5 is essentially that cleaned up Me 109. It has no antennas or gun ports or rivets or gaps . . . it's just what Hoerner wanted. It does all that is necessary to cut the drag in half, just like what happens on his imaginary, Super Me 109. So what happens to the interference drag on these two airplanes when you cut the drag in half? There's been no change in the shape, so the drag of the intersection will remain the same, but its percentage of the total drag of the new, cleaned up airplane will have doubled! Hoerner estimated that interference drag on the dirty Me 109 was 4.3% of the total drag of the airplane, so that means it goes up to 8.6% of the total drag on the Super Me 109 (roughly). Now, that's getting to be significant!

To add to that, here are some thoughts from Irv Culver who reminds us that interference drag can be very low if you get it right (or, even, negative; that is, the wing and fuselage together can actually have lower drag than the sum of the wing and fuselage measured separately). Or, it can be very high if you get it wrong (and both airplanes will look fine, unless you know what to look for). If it's wrong, you could easily double the drag (2 x 8.6% = 17.2%). But, if it's a good intersection, you could theoretically reduce interference drag to zero (or less). In our Super Messerschmitt, that would be the difference between no interference drag, and an additional drag equal to around 17.2% of the total drag, being generated at the wing root and added to the total drag of the airplane!

And all of this is happening in level flight. We haven't even begun to apply the back pressure on the stick that starts multiplying that 17.2% in some terrible, sickening way, until the airplane bogs down in its own over-expanded wake. When I designed the AR-5, I didn't fully appreciate how much this drag really did increase at higher angles of attack. I couldn't find anything definitive on it in my books, and none of the other designers seemed to know much about it. But, Irv tells a story about one designer's attempt to get his new ship off the ground, which he was unable to do until Irv came along



AR-6 Formula 1 racer design, showing wing/canopy relationship.

and made a new wing root fairing for it (an expanding radius one). The designer later became famous, but the interference drag caused by the lovely P-40 style, round-bottomed, tapered fuselage on this particular design was so great it had grounded the airplane. I didn't know exactly how much drag that was, but it sounded like something to pay attention to, if you ask me.

"INTERFERENCE DRAG GOES UP APPROXIMATELY AS THE SQUARE OF THE CL"[9]

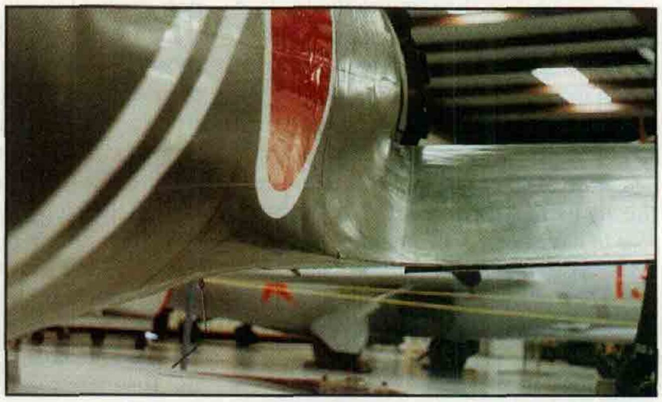
Whamo! I've been reading Hoerner now for about 15 years. I do it for fun. Sometimes I'm just looking up something out of idle curiosity, trying to get some minor little thing clear in my mind, when something comes right out and smacks me. I love *Fluid Dynamic Drag* for that. In it, a few years back I came across this line about how interference drag goes up with increases in lift. I had just finished reading an article by Stan Hall in ***Sport Aviation***[10] about the importance of high aspect ratio wings on Formula 1 airplanes. He had pointed out that, because a pylon racer spends so much of its time turning, it had better have low drag in the turns as well as on the straights, and that the way to do that was to reduce the Induced Drag (the drag induced by lifting) by using higher aspect ratio wings. He concluded that an 8:1 aspect ratio wing was probably a good compromise between strength, weight, and induced drag reduction. He showed how important induced drag was when you pull the stick back in a 3 G turn. That little 2% to 4% of the total drag of the racer that was the induced drag in level flight, suddenly becomes 9 times greater in the turn! It can add a third or more to the total drag of the airplane! That's like throwing out speed brakes in every turn! Induced drag goes up as the square of the lift coefficient (CL) goes up. That's a terrifying rate of increase, but it's in all the books. It's an easy thing to calculate. Nobody questions it. It's why sailplanes that operate at slow speeds (and high lift coefficients) have long, skinny wings.

So here I am reading Hoerner one night, poking around for crumbs in the Interference Drag Chapter, when I see this ratio again, "Interference Drag goes up approximately as the square of the CL." Only this time it's interference drag that's going up at that dizzy rate, not induced drag. Amazing! I hadn't seen that anywhere else before. It was Hoerner all the time!

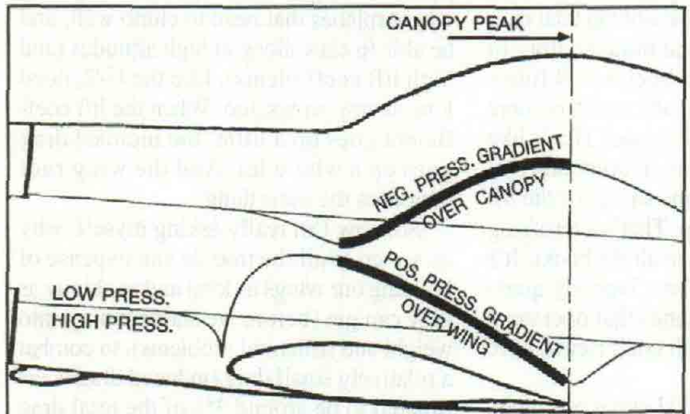
If this is correct, or even close to it (not all engineers take Hoerner as gospel), it means that not only does induced drag (the drag you make the wings skinny to compensate for) go up 9 times in a 3 G turn — now, he's telling me that wing root interference drag goes up the same dreadful amount! Worse even than I imagined! And, of course, everything that's true in a high G turn is true in a climb too because, after all, when you pull a 3 G turn, you're just climbing around in a circle. That's why airplanes that need to climb well, and be able to claw along at high altitudes (and high lift coefficients), like the U-2, need long skinny wings, too. When the lift coefficient goes up a little, the induced drag goes up a whole lot. And the wing root drag does the same thing!

So, now I'm really asking myself, why do we go to all the trouble and expense of building our wings as long and as skinny as they can get (before we start running into weight and structural problems), to combat a relatively small drag (induced drag is estimated to be around 3% of the total drag of the AR-5, at top speed), and not pay the same amount of attention to interference drag (as previously mentioned, thought to be about 4%-6% on most modern, low wing airplanes, at high speeds), which is

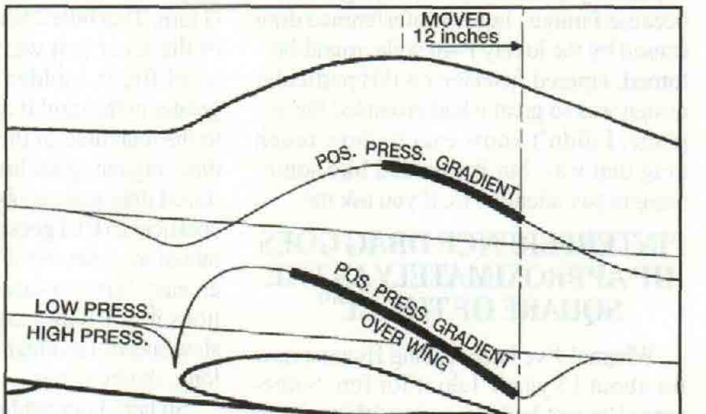
Arnold AR-5, Mitsubishi Zero, and Supermarine Spitfire, showing expanding radius wing root fairings. Rounding the trailing edge of the fairing as it blends into the fuselage (as on AR-5 and Zero) helps prevent early stall (and also allows a shorter fairing).



Arnold AR-5



AR-5, climbing, showing "inverse pressure gradient matching" as I think it should be (gradients canceling each other).



AR-5, with canopy moved forward just one foot, showing pressure gradients lined up (adding to each other. Boo!).

larger, and which goes up the same way induced drag does, at the same time (that is, at higher Cls, as when taking off, climbing, turning or flying at high altitudes)? Seems to me that low drag wing roots are every bit as important as long, skinny wings.

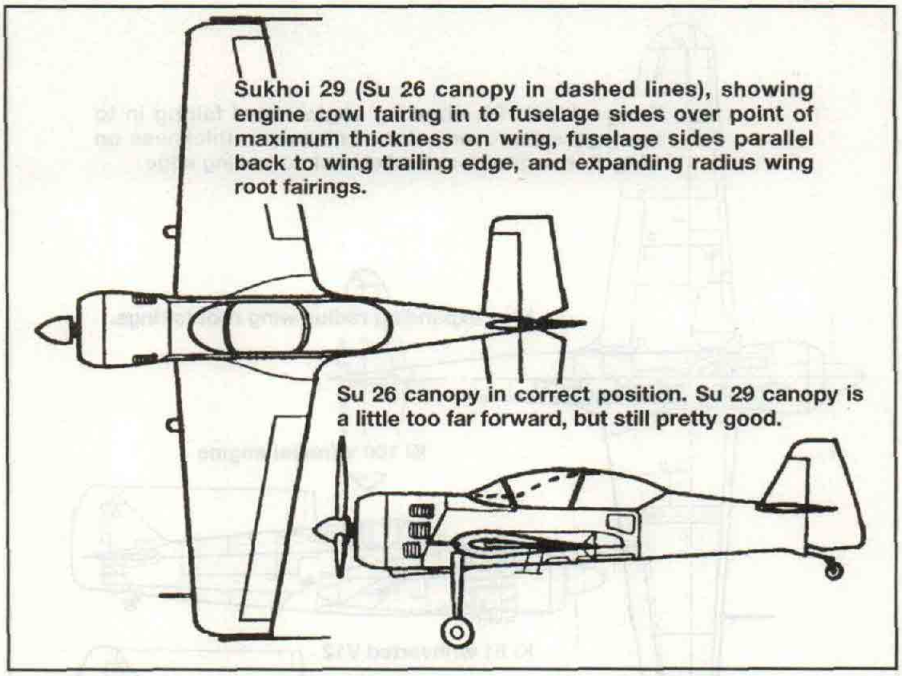
SEARCHING FOR REASSURANCE

When I designed the AR-5, I looked for any other examples of airplanes that appeared to be designed around the wing root as the AR-5 is. I found that the very successful Kawasaki Ki 100, Japanese Army fighter, had straight fuselage sides from the thickest point on the wing to the trailing edge, and that the radial engine was faired into the fuselage sides before the thickest part of the wing, as I had come to believe it should be. But the airplane was a modification of the Ki 61 "Tony", an inline engined fighter, so of course the fuselage sides were already narrow and straight. It doesn't appear to have been done on purpose. It just worked out that way. The airplane had a very good rate of climb though. And, even though the bulky radial engine increased the frontal area and wasn't nearly as streamlined as the inline engine, the speed remained about the same. Interesting, but it's hard to draw any conclusions from it.

Although it doesn't show in most drawings, the F8F Bearcat's otherwise compound curved fuselage is flattened noticeably on its sides, over the wing, from the leading edge, all the way back to the trailing edge. This was obviously done on purpose. Grumman went to some trouble to do it. But the canopy isn't placed exactly where I think it should be and, as was customary on mid-wing designs back then, it doesn't have any wing root fairings, at all. (Hoerner's data[13] indicates that, even a constant radius fillet, all the way around the wing root reduces drag on a flat tunnel wall. He recommends a radius of around 6% of the wing chord at the root.) They paid some obvious attention to interference drag at Grumman. Somebody knew something.

The F4U Corsair has the canopy in nearly the right place, but I didn't find any other low wing airplanes that kept the fuselage sides parallel. There are abundant examples of expanding radius fillets, though. I think they're mostly attempts to cure the results of contracting the fuselage too early. Spitfires, P-40s and Zeros had nice ones.

It wasn't until after the AR-5 had flown, when the Sukhoi 26 and 29 aerobatic airplanes appeared, that I found another similarly designed, low wing airplane. And it wasn't really even a low wing. It's a sort of low/mid-wing configuration. But, nevertheless, it's all there: the radial engine cowl, wider than the fuselage, fairs into the fuselage sides and completely by the time it is directly above the thick part of the wing, and the fuselage sides remain parallel from that point back to the trailing edge, just like the AR-5. The beautiful, blown canopy starts at the same point, over the thickest part of the wing, and it peaks over the wing's trailing edge, on the single seat Su26. The Su29, a two-place airplane, shows that even two and four seat airplanes can have this kind of wing body configuration, although the canopy peaks a little too far forward on this airplane. Both airplanes have expanding radius fairings, like mine. Someone over there in Russia must have thought interference drag was pretty important. But I really have no idea if they did all this for the same reasons I did, or whether it just worked out that the pilot's head was directly over the wing's trailing edge, so that's where they put the canopy. And, maybe it was just easier to keep the fuselage sides parallel. But the airplane is known for its exceptional rate of climb and unusually good vertical performance (where you have to pull up really hard and hope you don't scrub off too much speed in the high G pull up). Could they have done some tunnel testing over there and discovered the perfect placement for the canopy to reduce interference drag? And it turns out to be right where I thought it should be all along? And the people with bags of money are going over there, now?



Sukhoi 29 (Su 26 canopy in dashed lines), showing engine cowl fairing in to fuselage sides over point of maximum thickness on wing, fuselage sides parallel back to wing trailing edge, and expanding radius wing root fairings.

Su 26 canopy in correct position. Su 29 canopy is a little too far forward, but still pretty good.

Anyway, I was just working on a strong hunch when I first laid the AR-5 out. The wing aspect ratio is 8:1, which brings the span loading down to 31-1/2 lbs. per foot, so I knew the induced drag would be low. That's the one that's easy to calculate. And, as I've been saying, I believed the wing root interference drag would be very low, too. I just didn't know how important it was. I have no way of finding out, for sure, that it actually has very low interference drag, but Peter Lert was surprised at how hard he had to pull in a vertical bank to get the airspeed to start bleeding off[11]. And the airplane does climb at 1100 fpm on what I figure to be not more than 50 hp (at 5600 rpm). And it also turns out to have astonishingly low drag numbers for a small, fixed gear airplane: CD wing area = .016, CD wet = .0037, total Drag Area = .88 sq. ft. Aerodynamicists say these are among the lowest numbers they've ever seen for a propeller driven airplane, retract gear or not.[12]

THE AR-6: AN AIRPLANE THAT NEVER WAS

When I sat down to design the AR-6 in 1993, I was as convinced as ever that it should be designed around the wing root, as the AR-5 was. Everything possible had to be done to reduce interference drag, as well as induced drag, on the AR-6, because it was to be a Formula One air racer and, as Stan Hall pointed out, it would spend a lot of its time pulling fairly high G loads in turns. If the interference drag were high, it would not only be slower on the straightaways, but it would bog down as the drag built up in the turns. I'd designed the AR-5 back in 1981, and I intended to use everything I'd learned since, on the AR-6. It was to be my "interference drag tour de force." I started by reviewing what I knew.

Hoerner says that most of the drag we're worrying about (the kind that goes up at that dizzying rate as the lift coefficient goes up) is generated over the aft section of the top of the wing, where it joins the side of the fuselage. It's easy to see that the steep, positive pressure gradient (decelerating air, increasing in pressure) that already exists over that portion of the wing's airfoil, is made even steeper by the presence of the fuselage. I can see two ways, right off:

1. Even if the fuselage sides are straight and parallel (like the tunnel walls Hoerner[13] uses as an example), skin friction will slow the air as it flows along the side, adding to the deceleration over the wing, and steepening the drag-producing positive pressure gradient.

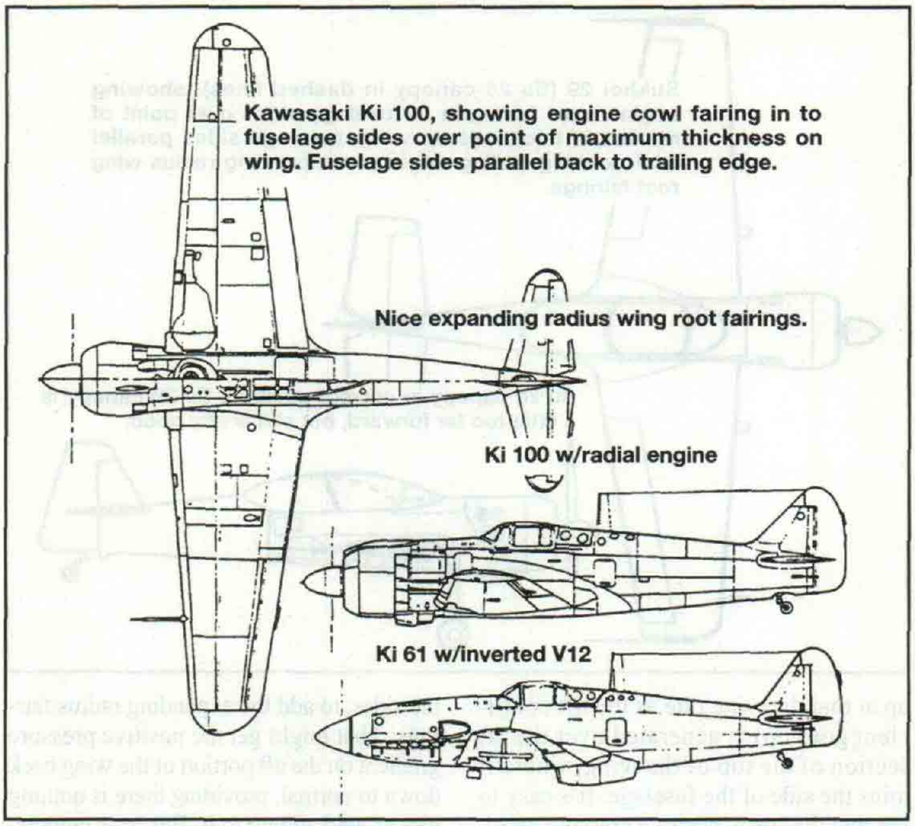
2. If the fuselage sides start coming together before they've reached the trailing edges of the wing (as they do on almost all the low wing designs I've looked at), the reduction in fuselage cross sectional area over the aft portion of the wing will further slow the flow, again steepening the dreaded positive pressure gradient. This is why that other airplane wouldn't get off the ground until Irv used an expanding radius fairing to fill in the space left by the contracting fuselage. Without the fairings, when the nose was brought up to develop maximum lift for takeoff, the already-high interference drag skyrocketed.

My solution to these two problems — just to get things back to where they were before the fuselage was added to the wing — is to keep the fuselage sides parallel from the thickest part of the wing, back to the trailing edge; and to make up for the deceleration caused by skin friction along the sides, to add the expanding radius fairings. That might get the positive pressure gradient on the aft portion of the wing back down to normal, providing there is nothing else around adding to it. But Irv's tantalizing suggestion that interference drag can be made negative ("You can make the wing think it's skinnier at the root") made me look for more.

I drew an approximate curve over a side view of the old AR-5 that plotted what I thought was the pressure distribution over the top of the fuselage. I "eyeballed" it by looking at other similarly-shaped airplane's pressure distributions, and by remembering that pressure is low on outside curves, high on inside curves and, finally, that it rises on the aft portions of streamlined bodies where they contract. Then I drew the pressure distribution of the wing at its root as I thought it would look in a climb.

When I put the canopy and wing pressure distributions together, I looked to see how they lined up and, behold! . . . the high pressure area at the front of the canopy is directly over the low pressure area on top of the wing, and the low pressure area over the top of the canopy is directly over that bad old high pressure gradient over the aft section of the wing. They work to cancel each other out when they're lined up like this — to reduce the steep angle of the positive pressure gradient on the aft section of the wing.

But, notice what moving the canopy forward or back even a little from this position does. Instead of canceling, the pressure fields add to each other where they overlap on the fuselage side, steepening the positive pressure gradient over the



Kawasaki Ki 100, showing engine cowl fairing in to fuselage sides over point of maximum thickness on wing. Fuselage sides parallel back to trailing edge.

Nice expanding radius wing root fairings.

Ki 100 w/radial engine

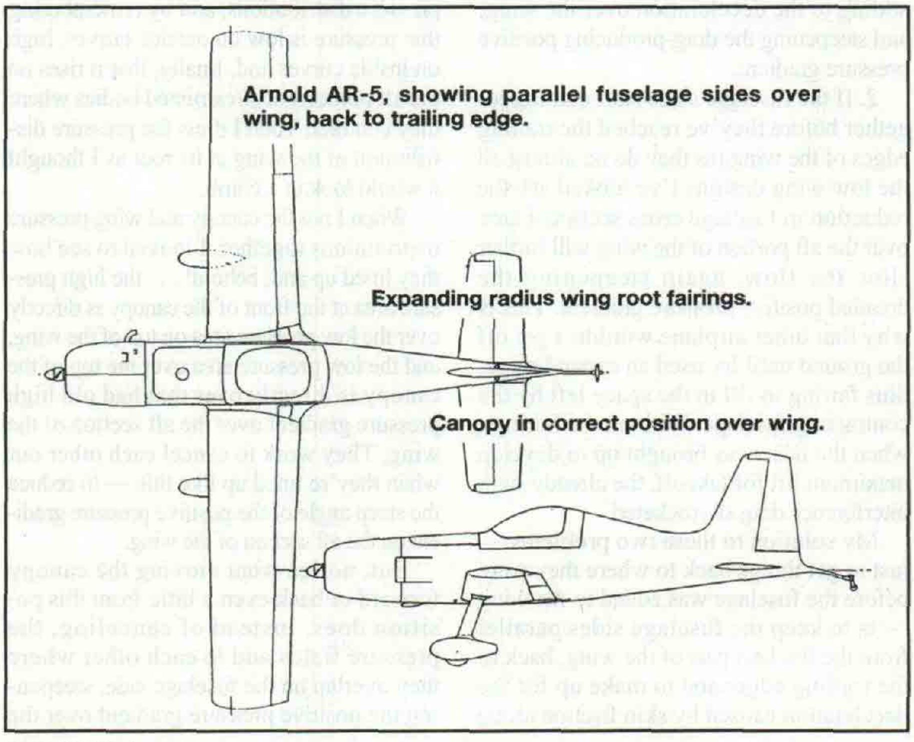
Ki 61 w/inverted V12

trailing edge. I think getting this alignment right helps explain why the exhaust streak that forms on the AR-5's fuselage side is so straight when compared with exhaust streaks I see on other low wing airplanes. The others all take a dive over the aft portion of the wing, but on the AR-5, the sooty flow stays up high and runs smack into the horizontal tail (I didn't expect that). I believe matching the pressure gradients inversely by putting the canopy in the right place (and not contracting the fuselage too early) prevents drag producing separation, reduces cross flow on the fuselage, as well as drag caused by needless expansion and contraction of the flow (pressure drag). But, I'm still just guessing.

The AR-6 has that big wide Continental O-200 in it. While keeping the cowl as small as possible, I also tried to make it as full and round as I could to minimize the variations in velocity near the propeller, and to avoid the drag caused by the intersections of "blister" cowls. I used its full shape to create another high pressure area over the front part of the wing (over the wing's low pressure area) by fairing it into the fuselage sides over the airfoil's point of maximum thickness (inside curve = high pressure). The big cowl also allowed the use of a tuned exhaust system under the engine. To avoid problems caused by the high pressure peak at the stagnation point of the wing's leading edge colliding with the high pressure caused by the contracting cowl, I kept the sides of the cowl straight and parallel at the bottom and made a little leading edge fairing out of it to soften the impact at the wing root. Bruce points out that it's important to keep the bottom corners of the fuselage rounded near the leading edge to avoid tripping the flow of high pressure air that comes from under the fuselage when the nose comes up. Irv cautions that there isn't as much to gain playing with the area forward of the point of peak velocity (over the thick point on the wing) because things kind of take care of themselves up there. The air makes its own fairing, so to speak. But, I think if there's a bump that has to be somewhere around there anyway, like a cowl or a canopy, why not put it where it'll help, rather than hurt?

The canopy, of course, is shaped and positioned to provide high pressure over the low pressure area of the wing, and low pressure over the positive pressure gradient that peaks at the wing's trailing edge.

You'll notice that the tail surfaces on the AR-6 are rather large for a Formula One air racer. I found that the pitched and yaw stability margins of the AR-5, even though I used large tail surfaces *and* the tail arm was a normal length were less than I thought they would be. I knew that the long nose was going to be destabilizing, but there's more. Hoerner explains that expanding radius fillets at the wing roots are destabilizing in that they move the aerodynamic center of the wing back at the root[14]. I would expect that this is also true for the rest of the stuff we've done at the wing root. Nothing's free! If you're going to use inverse pressure gradient matching on your design, be prepared to use somewhat larger tail power coefficients (I'm guessing, maybe 5% higher) than you would ordinarily. I think this is a more-than-fair trade though, considering that tail drag doesn't go up the way



Arnold AR-5, showing parallel fuselage sides over wing, back to trailing edge.

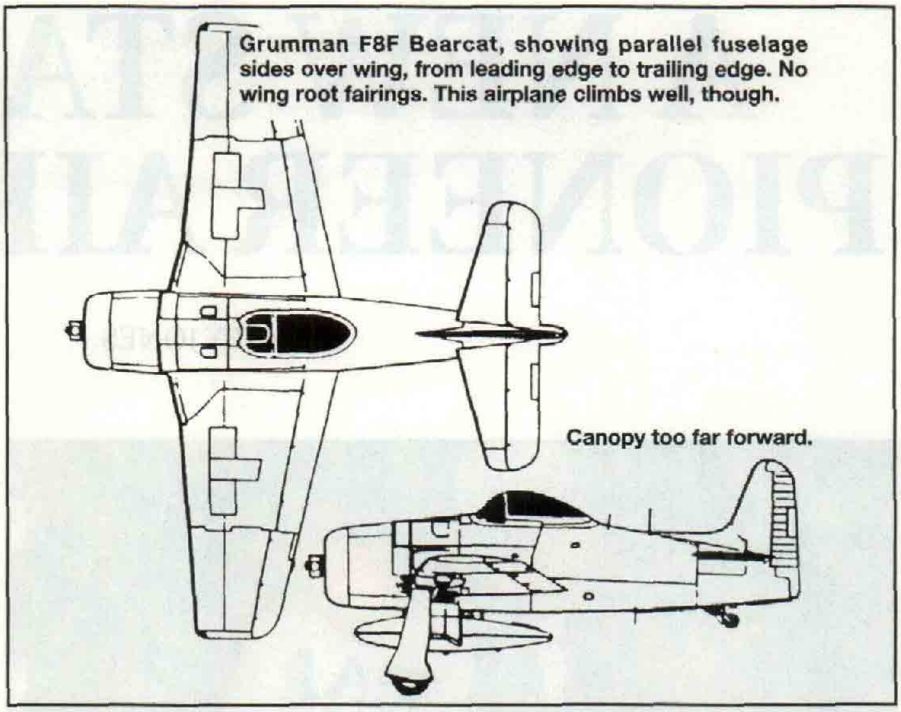
Expanding radius wing root fairings.

Canopy in correct position over wing.

interference drag and induced drag do (with increases in lift).

Although interference drag isn't as high on tail sections because these intersections are operating in the much slower moving air of the fuselage's thick boundary layer, I saw an opportunity to use some more "inverse pressure gradient matching" (I've asked others what I should call this thing . . . this seems to describe it as well as anything) here too, by placing the high pressure area of the horizontal stabilizer in the low pressure area of the vertical stabilizer. Can't hurt. And I tried to position the wheel pants so their point of maximum thickness was directly below that high pressure peak that forms at the leading edge of the wing, just as I did on the AR-5. Harry Riblett thinks this is a good idea, too. He's the only one who's noticed it. We think using inverse pressure gradient matching here softens the impact of the wing's leading edge (or it could just reduce the drag of the wheel pants — either way is O.K. with me).

I was inspired to design the AR-6 by Formula One pilot, Troy Channing, whom I'd met at Oshkosh in 1993. I was just starting detail design when Troy was killed in a Mustang II near Livermore, CA and I never got enthused enough again to finish it. But, I refer back to the model to remind myself what inverse pressure gradient matching looks like, if taken seriously. I offer it here for the same purpose.



Grumman F8F Bearcat, showing parallel fuselage sides over wing, from leading edge to trailing edge. No wing root fairings. This airplane climbs well, though.

Canopy too far forward.

IT SOUNDS LIKE AREA RULE

In my January 1993 article in ***Sport Aviation*** (*Getting the Most Out of 65 HP*) I said that I had arranged the wing, canopy, fuselage and wheel pants so they formed a sort of "poor man's area rule." I had read somewhere that John Thorp had said that about his T-18 design.

Aerodynamicists quickly pointed out that "Area Rule," strictly speaking, was only valid for the transonic speed range, and that it was misleading to say that I had applied it to reduce drag in the subsonic regime. Area rule says that airplanes designed for transonic or supersonic flight should have their **total** cross sectional areas expand and contract smoothly along their lengths in order to delay and reduce the dramatic drag rise that occurs just as the airplane nears the speed of sound. If followed as a "rule" it would have me subtract the total cross sectional area of the wing (for example), from tip to tip from the cross sectional area of the fuselage in order to keep the total cross section of the airplane from suddenly increasing in the presence of the wing. If I subtracted the whole cross sectional area of the 6" thick wing on the AR-5 from its fuselage, I wouldn't have any fuselage left! This is why supersonic airplanes have such thin wings (and coke-bottle shaped fuselages).

But, I didn't have to compensate for the **whole** wing on the AR-5, because in subsonic flight things work differently. Below transonic speeds (under, say, 350 mph), the fuselage doesn't feel the presence of the wing out toward the tips because pressure, at that speed, dissipates rapidly in all directions as it moves away from its source; unlike what happens in the flat, compressed, disc-like form pressure assumes at transonic speeds. At slower speeds I only have to consider that portion of the wing that is in the near vicinity of the fuselage. It's not altogether different, but different enough.

So, discouraged from referring to it as "area rule" any longer, I now call it "inverse pressure gradient matching," and everybody's happy. It more closely describes what I'm doing anyway.

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