The Horten H X Series: Ultra Light Flying Wing Sailplanes

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As background into what got him started preparing this presentation, Al said it all started when he heard about the 1997 National Soaring Museum Flying Wing Symposium in Elmira, New York. With his fascination of flying wings since his childhood days, he decided to get his foot in the door and sent a letter to Paul Schweizer to see if he could get a slot on the podium. Al had been working for the past couple of years on the blended wing body, which is a flying wing design NASA has had some interest in. After consulting with Bruce Carmichael and several others, Paul approved Al's request to put on a presentation on the history of Horten flying wings.

Al began be giving an introductory overview of what would be covered in the next hour or so. This was done in the form of a narrative at each of the bullet points on the slide.

The more he dug in the Horten history the more fascinating it became for several reasons. As a little bit of preliminary history, he commented that in the early 1920's, particularly in Germany, sailplanes were trying to achieve higher and higher aspect ratios. It turns out this has a theoretical basis in spanload history and during this period, after WWI and early 20's, they developed the optimum span load and found out how to calculate what the induced drag was on a wing. Induced drag was sort of a big problem at the time and so spans on sailplanes became larger and larger as they found how to make the limited structures they had work at the time.

The other half of this occurs in the late 20's the Hortens come along as students in the glider clubs and then in the early 30's as sailplane builders. They came up with a different emphasis on the particular, more classical spanload of the day by coming up with their now famous bell shape spanload distribution theory. More on this later.

The next area to be covered is some history of the Horten's sailplanes over the years. He believed Peter Selinger had identified 43 particular sailplanes the Horten brothers had built and, he felt this had a strong influence on how they ended up where they did when compared with others of the time like Jack Northrop. This history would include the high performance sailplanes, some of the later designs while Reimar was living in Argentina, and in particular, the foot launched Horten H Xc which is the ultimate goal of the presentation.

Horten Flugzeuge

He then began talking about the analytical span load history. The original formulation for this comes from Ludwig Prandtl who came up with a paper published in Germany in 1918 and in an English version by NACA in 1920, called "Applications of Modern Hydrodynamics to Aeronautics". In this he explained how to calculate induced drag based on spanload using a lifting line theory, which assumes all the lift occurs along a single spanwise line called the Line of Aerodynamic Centers. The way he accomplished this was with a series of chordwise vortices along the wing's span. He mathematically modeled these horseshoe or closed loop vortices going all the way back to where the wing first develops lift, which is a starting vortex. If you moved the wing in a perfect fluid without viscosity this vortex would remain there as has been shown in some experiments. However, it is difficult for most people to visualize a wing and think about the flow going backward underneath it, so it is really more of a mathematical concept with some basis in reality.

Max Munk applied calculus to this theory and one of the things he came up with was the optimum span load that minimized the induced drag. The optimum span load turned out to be the elliptical span load distribution. This theory is taught all through aeronautical engineering school as the optimum so everyone is inclined to accept it as the best way to go as long as you are working in an inviscid world. However, there have been some recent developments done by a small group of people at NASA Langley where they have applied viscosity to this theory and it turns out that the optimum is almost, but not quite purely elliptical. So for all practical purposes, modern designers still use the elliptical theory and it works very, very well.

The problem was this is a very mathematically intensive way to try and calculate the spanload in order to get a beautifully elliptical span load that is desired. Oscar Schrenk came up with a very simple method of predict what span load is, but Al warns that this method is what would be called a "Rule of Thumb". It works very well, but there is no firm theoretical basis for the way it works. There is some empirical evidence that it works very well, but it just happens to work out that way. Referring to the Analytical Span Loan History chart, Al described the individual lines representing twist, taper and surface deflections and then that they look like when combined under Schrenk's method. The twist line has a distinct jog in it that is the result of a flap being deployed in the inboard section of the wing, which is representing mechanical twist, so this method deals very well with control surface deflections.

The other primary line on the chart represents the planform of the wing based on the "Rule of Thumb" of an elliptical distribution. It is an average of what you have for a plan-form and the elliptical distribution. The two lines, twist/deflection and plan-form, are then combined yielding the third, more complex representation based on the angle of attack. This particular chart was done to try and find where the wing would stall first and as it turns out it is at the inboard end just before you get to the flap. The chart also shows finite span load at the tip, which realistically cannot exist since it is a discontinuity of nature and is one of the problems with Schrenk's approximation method. However, Schrenk's method was used by most people very easily mathematically, this being a relative term, to calculate the span load for their aircraft.

Unfortunately, Schrenk's formula didn't give the full picture since there were some problems with it, and one of the people who came up with a solution for this was Hans Multhopp. He simplified it mathematically by adding control points in his wing, which allowed him to get a product condition. This is were the flow comes off the upper and lower surfaces cleanly and joins the air stream. These control points are simply vortices going the other way and Multhopp put them coincidence with the circulation vortex along the line of aerodynamic center. In 1944, Laska and Weissingger move the control points back to the 75% chord position versus the 25% position of Multhopp's which is where the normal aerodynamic center is assumed to occur, however, this makes the method even more mathematically intensive. Don't forget this is at a time before digital computers which made performing the calculations much harder accomplish with accuracy.

Multhopp's "simplified" theory came out in 1938 and the Horten brothers saw it as a big jump forward in being able to understand the span loads of their airplanes. You can understand why when you start thinking about the bell shaped span load. The bell shaped span load by definition goes to zero at the tip, so Schrenk's method which has a finite value for span load at the tip is very difficult to deal with. This made Multhopp's method a big break through for the Hortens and all their designs since 1938 used his theories in the design method.

In talking about bell versus elliptical span loading, elliptical is the optimum since it gives you the minimum induced drag and for sailplane designers this is a big deal. The Hortens thought that may be there are times you don't want the optimum for one thing, but a sub-optimal solution for many things will solve more problems so they came up with the bell shaped span load. Al referred to the Bell vs. Elliptical Span Loads slide to illustrate this point. Both the elliptical and bell shaped curves come to a finite point at the tips which is very important. Once you have these span load distributions, the fascinating piece is that you calculate the induced drag for each of the little vertical areas on the chart as you progress across the span.

On the elliptical curve the induced drag continues to build all the way across the span always represented by a negative value, which is drag. On the bell shaped curve you notice there is a positive area out near the tip that has become what could be called induced thrust versus being drag. This allows you to do things like proverse yaw with the roll command, which is based on the amount of lift that is generated. By making more lift at a tip then the value of the induced thrust will increase at that tip. Phil Burgers noted that this induced thrust condition is why birds fly in the "V" formation. The birds at the tips of the "V" are actually achieving forward thrust, whereas the lead bird is not but does benefit from the significant up-wash from the others. So, in 1938 the Hortens are using this induced thrust at the tips, but we don't see it again until the 1950's when Dick Whitcomb came up with the winglet designs. Phil Burger pointed out that the wing tips on Horten's aircraft are similar to "flat winglets", which Al agreed with.

The one thing that Multhopp's method cannot account for is the sweep angle, so there is a residual value out there that the Hortens called "mitteleffekt". This is purely an artifact of their calculation method and it doesn't really exist since it involves a problem in the analysis technique, but not in physical reality. As you sweep the wings back on any type of wing up-wash from the center influences the tips differently so there is a small increased load at the tips and a decreased load at the centerline. In Multhopp's technique the up-wash for sweep is unaccounted for and the next slide showed what this looked like. If you took a Horten wing and un-swept it the results would be shown as the solid line on the chart which has a fairly low lift value at the tip but a much higher value near the middle relative to the swept case and this is the mitteleffekt. Bruce Carmichael commented that Irv Culver's approach to fixing this problem was to increase the angle of attack of the center section, whereas, the Hortens fixed it by increasing the chord at the root section. So, mitteleffekt is not the sag in lift distribution at the middle, but it is the unanticipated sag in the lift distribution in the middle, just to clarify the point.

There is one other piece of the puzzle in the calculation method used by Multhopp. Al had seen it in many of the Horten papers, but it wasn't explained very well. Then he ran across some unpublished papers by Dr. Edward Udens in Germany, who has a lot of information on the Horten designs. The Calculation Method (Multhopp) slide shows the analysis derived by Dr. Uden's (see next page for an illustration of this technique). It maps the wing out using a uni-circle arc that begin with a value of zero at the root and rotates around to a value of one at the tip. This 90-degree segment is then divided up into equal angles and then the arc intersection points are mapped down through the wing's chord. These give you the spanwise locations that are called control points for analysis and are labeled as the central difference angle. These sometimes showed up in the Horten papers as a delta. What Horten found was that when you raise the power of the transcendental (sine) function for the value of 'n', you get closer to a bell shaped lift distribution curve. If you make the 'n' value 1 then you end up with an elliptical distribution and, when you raise it to 2 it becomes bell shaped but you still don't have induced thrust at the tips. As you get to a value of 2.5 there is a crossover from adverse yaw to proverse yaw and, as 'n' increases towards 3 you get increases in induced drag, which is the penalty for this method. So you want the minimum value of 'n' you can get away with and for the Hortens most of the time in their designs this value was 3, which is near optimum.

At the bottom of this slide is a span versus twist graphic, which represents a correction for the chord length. The graphic is the twist distribution for the Horten H Xc and was provided by Reinhold Stadler in Germany who has a program for calculating it quickly and easily. The fascinating thing about all this to Al is that there is wash-in for about the first 20 percent of the wing, so the wing is twisting the wrong way. Then it goes out to about 10 degrees of washout at the tips, but overall it has a twist range of about 11.7 degrees due to the wash-in area.

Udens took this analysis technique and using a value of 3 for 'n' and calculated the span loads for a number of different configurations (represented in the Udens' Results slide) including the induced drag. Then he found if you had a control surface deflection for those particular span loads you could determine the yawing moment for the designs. He did this analysis for eleven different designs and looked at the affects of elevon configurations. He found that even with a bell shape curve and a deflection of an inboard elevon would cause adverse yaw as represented by the negative numbers in the results chart. The positive numbers represent proverse yaw. Al offered a caveat at this point that was brought up during the SHA session; proverse yaw is not always desirable. When you look at the Military Standards (Mil Std) used throughout the government for handling qualities for the same level of adverse and proverse yaw, pilots find the proverse yaw more objectionable. So, just because you can get proverse yaw it is not necessarily a good thing, and getting any degree of proverse yaw is hard. Adverse yaw is usually the norm as can be attested by many sailplane pilots who have run out of rudder authority when using full ailerons.

Al again referred to his slide showing Udens' eleven different aileron/elevon configurations to further illustrate his point on proverse and adverse yaw (see top of page 3). As more of the elevon surface is moved outboard the amount of proverse yaw increases. Udens wanted to confirm these findings so did two configurations, elliptical and bell shaped, and found they definitely had adverse yaw as noted for examples IV & V on the slide. The conclusion here is that inboard elevons for roll control are not necessarily a good thing since they produce more adverse yaw. The proverse moments become larger and larger as more of the elevon surface is pushed out towards the wing tip. It occurred to Al later that perhaps you could blend the out- board roll control surface with an adjacent elevon; and with the right amount of movement on each surface produces a fully coordinated turn. However, there is another piece to this puzzle and that this is applicable to only one particular spanload. If you change the amount of lift you are asking for, how does it affect the yaw moment of the wing? Al couldn't find anything in the literature or Udens' calculations, so decided he would take it on as a project.

Al moved on to start covering the hardware aspect of the Horten's. His next slide covered the Horten H I, H II, and H III. The H I configuration was found to be all wrong with ailerons and an elevator in the middle. Trying to flair on landing had the predictable affect of actually dumping lift resulting in a rather hard landing instead of the gentle touch down trying to be achieved. Walter Horten had an interesting story about this problem that Al recommends everyone read. Walter also found that by pushing the stick forward slightly, he could fly in ground affect all the way down the runway. Since this obviously wasn't the way to go, the aircraft eventually ended up as a big bonfire.

With that experience behind them, in 1935 the Horten's build the H II with a bell shaped spanload and used some mathematical polynomial functions to get the spanload he wanted to achieve (the Hortens used Schrenk's method, as this was before Multhopp's theory). It was also the first time they used fully functional elevons in their design.

The H III was the next design that was looking for improved performance and a refinement in what they had found with the H II. This was also the first airplane they flew in the semi-prone position, since the previous models had a more conventional upright pilot seat.

The H IV and H VI were the cream of the crop for the Horten's since they had an almost unlimited budget and very few constraints on the design objectives. The H IV had a high aspect ratio and increased performance and most important was extensively tested producing a lot of hard data that could be used to improve future designs. The max L/D for the design was to be 37:1, but DFS testing only produced a figure of 32:1 and MSU came up with 29:1. Al felt the lower number found by MSU may have been to a misreading of the elevons, because the data the Dez Georges-Falvy published never showed the elevons reaching zero all the way across the wing at any time. This may have been the result of mis-rigging and/or due to some of the other work done to the airplane that might have changed the spanload somewhat.

The H VI (only two of which were built) had an extremely high aspect ratio, but the performance was truly limited by the structure of the aircraft. It had two separate flutter modes that were excited at speeds that it commonly flew at and the only way to handle them was to fly through them. The "Mitteleffekt" solution was the addition of the Horten mini-tail that increased the area near the centerline of the wing to try and make up for the loss of lift they found in their analysis technique. The Hortens sort of thought the airflow was kind of colliding in the middle causing some turbulence that was creating the loss in performance they were experiencing. So they were trying to straighten out the quarter chord line from one side to the other, which was the case with the H IV. The H VI, if you plotted it out the quarter chord, actually went backwards which was an experiment whose results were inconclusive (today it is understood that the "Mitteleffekt" is an artifact of wing sweep). They did make one other sailplane that unfortunately never flew, the Horten Parabel, that would have proved to them this was not the problem (it, like the H I, ended up as a pile of ashes).

At the end of WW II, Germany was restricted from flying sailplanes and Reimar Horten ended up moving to Argentina to continue with his work, although there were some constraints on his ability to produce some of the designs. He did some amazing work considering the circumstances and the H XV series of three aircraft were certainly among his best. Al commented that Paul MacCready flew against the single seat version during the world championships and some day he is going to try and get Paul's reaction on what they were like flying with them.

One of the designs Al particularly liked was the H XVc (I. Ae. 41 Urubu in the Argentinean designation system) and he mentioned that a friend of his at a technical school in Buenos Aires was in the process of restoring one. Apparently all the H XV series of aircraft suffered some type of aeroelastic handling quality problems where a little bit of input got no response, but when the input was further increased all of sudden the aircraft responded very quickly. This created a tendency for PIOs. Joe Alvarez of SHA indicated the best way to fly them was by making a large input and then taking it out right away, which would allow you to fly the airplane relatively well. Al felt that with modern day construction materials the problem of aeroelasticity would become manageable.

About this time there was some emphasis on coming up with smaller and lighter sailplanes. Bruce Carmichael had mentioned this earlier in the program when he commented about his last trip to a soaring symposium at Elmira. To this end Horten designed a series of ultralights designated the H X, which was a recycled number so you have to be careful about which H X series you are talking about (the Horten X of WWII was supposed to be a supersonic jet).

The H Xa (L'Alita) at 7.5 m span was relatively small even by hang glider standards. It used Frise elevons (leading edge dips down into the airflow as the control surface is moved up creating more drag on that wing), was flown extensively, but didn't have a fully developed bell shaped spanload distribution. Reimar was afraid that with a fully developed bell shaped distribution he wouldn't have enough lift to get the pilot off the ground as a foot launched sailplane like he wanted. Although the H Xb was never completed, the design had a fully developed bell shaped spanload, so Horten put on plain elevon surfaces. He wanted to use the H Xb as a test bed for his ultimate foot launched goal, which was the H Xc (Piernifero 3). The H Xc also was never constructed and exists only as a design study but was to be very, very high performance with a projected L/D of 30:1 and a minimum sink of 80 fpm [AHB: Recent sleuthing has uncovered an Australian built version of the H Xc which is built from composite and currently being flown by Bill Moyes]. These figures are better than the current Carbon Dragon design (25-27 L/D & 100 fpm) and capable of micro-lift soaring.

Al looked at Horten's performance prediction with some skepticism, since in the past Reimar's design projections had come out somewhat lower in actual flight tests. The H Xc is very labor intensive to build since it encompasses 72 ribs over a 15 m span with a proposed weight of about 90 lbs. This makes it very complicated and difficult to build to the standards envisioned by Horten. Bruce Carmichael offered to put the weight of the H Xc in perspective with Danny Howell's Light Hawk. It is built with the very latest in composites over a 15 m span and is projected to come in at about 150 lbs, with a boom and tail surfaces.

Al commented that Horten had painted himself into a very difficult corner with the design criteria, but both Al and Bruce mentioned that lowering the design load might make the difference. However, there was some concern about such a structure holding up under the loads that could be imposed by trying to launch into some of the Owens Valley lift.

Someone asked what construction materials were planned for the aircraft. Al noted it was classical wood and fabric, and that Horten's other designs using the same materials had all come in pretty close to the projected design weight. The difficulty becomes one of how much do you give up in structural rigidity and ultimate strength. The pencil drawing of the aircraft done by Jan Scott, with the help of Reimar, shows the pilot with a parachute, so maybe there is another story here we don't know about.

There was a lot of thought that went into the design. One item was the center stick connected to a push rod going out to the elevons. The mechanism was set up so that the lateral movement of the stick produced a 3:1 ratio to the aileron function and a 1:1 ratio to the elevator function. Unfortunately, there are only some unpublished notes by Dr. Horten that don't show the degree of detail Al would like to have seen for a better analysis of the aircraft's construction. But even with this limitation, Al is still hung up on this airplane, which is probably a throwback to his original hang gliding days in the 70s.

Someone in the audience asked which aircraft was being shown in its unfinished state on the slide. Al commented that it was the wing tip of the H Xb, which is now hanging up in a facility in Cordoba, Argentina. At one time Jan Scott had tried to purchase it, but ran into difficulties with export permits, which were further complicated by the Falklands war.

Al now moved on to the real meat of this presentation, an analysis of the H Xc based on the available information. The first thing he did was try to find some airfoils. The Hortens had used Gottingen airfoils throughout their careers so the H IV was probably a good choice for applying to the H Xc. He felt that the Horten's hadn't come up with any other airfoils in the few years between the aircraft. This became his baseline airfoil. The first thing he needed to find was the mean camber line in order to use the two analyzing tools he had at his disposal. He plotted the airfoil and had one of the programs create the camber line right down the middle of the airfoil (see top of page 5). He then wanted to determine if there is a function to describe the camber line and it turns out there is fairly easy one using a polynomial fit. Reinhold Stadler in Germany gave him the twist distribution data and he was ready to go.

The two pieces of the puzzle here are spanload information as to what the induced drag is from the vehicle and, what do you get for profile drag from the airfoil. This latter piece was solved with Dr. Eppler's and Dan Somer's PROFILE program which also handles control surface deflections. The other program computes the spanload and twist distribution and if you have the right mean camber line in it gives you the trim condition, pitching moment, rolling moment and induced yawing moment (the profile yawing moment had to come from another program). With components all over the place this project became a bookkeeping nightmare.

Al moved on to the Vortex Lattice Analysis, which does all these things, but the questions come up about proverse and adverse induced yawing moments as to the acceptable handling qualities. Trying to understand how the induced thrust makes it possible to get proverse yaw was a difficult concept for Al until he drew it out. If you look at the twist the Horten's used, you find very little twist in the center section. In fact, it washes in a little before it washes out very radically at the tip. This is in direct contrast to something like the Northrop designs that use nearly linear twist from the center to the tip. If you start the twist right away you don't get enough up-wash at the tip to produce the proverse yawing, but because the Horten's have almost no twist in the middle and then twist radically at the end, it pushes the up-wash out towards the tip. So what happens in Horten designs is if you look at the angle of attack you have a lift and drag vector with a resultant vector that is aft of the local angle of attack. That's always true even out at the tip, but if you have enough up-wash from the center section and you average what the angle of attack is for the whole airplane, then look at that relative to the tip, you find that the resultant is forward of the average angle of attack. If it is forward and you deflect the control surface downward then you increase lift and drag, the resultant gets bigger and the component of it that moves forward gets larger. This is what produces the induced thrust and how you get proverse yaw out of the wing. (Phil Burgers commented it was like a horizontal winglet and Al agreed. This is a crucial point and is an absolutely correct interpretation)

In order to get the results he wanted, Al used 320 panels (40 spanwise and 8 chordwise) which seems like a lot, but its not since a typical program today would use a million panels. He then put up the slide showing the results of his symmetrical span load analysis on longitudinal trim. He used a 14% CMAC location, which is probably about where Horten would have put it based on the middle effect numbers that he had at the time. The chart only gave Al induced drag but nothing on profile drag so he couldn't tell what the performance would be and what elevon deflections are needed to get certain lift coefficients.

Al moved on to the harder stuff, asymmetrical span loads (lateral directions). Here is where we start thinking about the amount of roll we get when the aileron is deflected. He likened this to the sailplane pilot moving the control stick based on the amount of roll he desires for a maneuver. There are some instances when the amount of roll can even exceed the capability of the rudder to handle it effectively. What isn't thought about in this type of maneuver is the amount of yaw it produces which has both an induced and profile drag component and these have to be added up to calculate the total component. There is also a change in the lift associated with this component. In order to overcome this, Al split the longitudinal trim into two and deflected them plus or minus two about that trim point. His graphs at this point illustrated the differences in these roll moments. The chart of lift coefficients and the resulting roll and yaw moments showed positive values for every occurrence until the final point of .198 CL which gave a -.00015 Cn (yaw moment). This indicates that the H Xc flies faster eventually it will get to a point where the adverse yaw will come up and bite you. He did point out that there are no aeroelastic considerations in these calculations, assuming that it is a rigid airplane, but also noting that this is not a good assumption for Horten's aircraft based on the construction.

There is a problem with this in the lift coefficient. As you increase lift you go to higher and higher angles of attack, increasing the dihedral effect, and this increases your dynamic directional stability. This means, conversely, that as you fly faster you have a decrease in the lift component which means you have the adverse yaw factor creeping in at the same time as there is a decrease in the dynamic directional stability. The end result is an aircraft that doesn't handle as well at the higher speeds. Phil added that by putting flaps down about 5 degrees you shift the CG aft a little bit to increase the up-wash at the tip as you increase the speed. Al noted this was one way of solving the problem, but again pointed out that it doesn't take into account the aeroelastics of the airframe. He referred back to the Horten aircraft with the two elevon surfaces and the inboard one could possibly be rigged to act as a flap to move in such a way as to minimize the impact of adverse yaw at higher speeds. This might not work real well for very dynamic maneuvering, but for trim conditions when running between thermals it might work very well.

Now he moved on to the airfoil analysis. He used the Profile program from Dr. Eppler, which had a flap option that gave nice clean little surface deflections to look at. He then took the vortex lattice results, looked at what the local lift coefficient was at seven span stations for each wing and matched these with the control surface deflections and then the profile drag. As a reality check he integrated the profile lift components from the Profile program to see what he got for his spanload distribution and, then went back to his vortex lattice program and compared the two results. At max L/D and lower lift coefficients he ended up with about a 2-3% error rate. He did two other steps that yielded up to about a 7% error rate with the differences being in the separation on the wing, since the vortex lattice can't handle the separated flow. The integrated lift coefficients matched really good so he could sum up both the roll and yaw moments based on profile curves since he knew where they were at the span stations.

Now we get to the bottom line. Remember the 30:1 and 80 fpm, well the maximum L/D Al got was 31.9 not including the drag of the pilot, with a minimum sink of 85.2 fpm, again not including the pilot. He felt that these figures showed Horten was in the ballpark with this aircraft.

The final thing that Al did was to approach it from the argument about the difference between an elliptical and bell shape lift distribution on the L/D. He stayed with the same airfoil, aspect ratio and wing area and did the calculation all over again. What he found was the elliptical gave about a 37:1 L/D versus the 32:1 of the bell curve, which is a 13% penalty using Horten's methods. The gains for an elliptical distribution come from longitudinal stability and lateral directional handling qualities. The only thing he didn't check for the elliptical was how bad the adverse yaw characteristics were, since you have to use a different planform to change the tip chord. Al commented that he had thought this aircraft wouldn't be worth building if it didn't get at least 30:1, and when his number crunching came up with 31.9 he said the people in his shop could hear him giving out a big whoopee.

In summing up the past hour or so, Al noted that the bell shaped span load produced proverse yaw at the expense of about a 13% penalty in drag. However, this was probably a good trade-off due to the other benefits gained and Reimar Horten was willing to live with the difference. Horten had been a student of Prandtl's elliptical span load theories, but chose to disregard them for his own bell shape distribution. You have to remember how much yaw you get out of a particular amount of roll so the differences between the Cnda/Clda have to be considered as engineers, in order for pilots to always have enough rudder. (Phil Burgers injected a little humor noting that in Horten designs you run out of rudder in a hurry.) Al thinks there is still some optimization of the up-wash distribution (sin^n), but this hasn't been done yet. He just assumed a value of 3, but Horten and Nickel have done some work with other values. You have to consider the effect of the coefficient of lift on dynamic directional stability and this may have been one of the problems with Northrop's designs when flying at higher speeds where the nose had a tendency to wander around a little.

His concluding remark was that the Horten H Xc is a very high performance ultra light sailplane and somebody has got to build one someday, since it's just too good of an airplane to let lay around on a piece of paper. He then thanked his list of supporters like: Bruce Carmichael for getting him into it: Dr. Paul MacCready for his help; Rheinhold Stadler for calculating the twist distributions; Gregg MacPherson (in New Zealand) for supplying the Udens notes; Juan Manuel Mascarello (in Argentina) for some of the Horten photos; Russ Lee at the Smithsonian for supplying the Horten airfoils; Geoff Steele for his support; Doug Bullard for help in scanning some of the photos; David Lednicer for coaching on some of the analysis pieces; Jan Scott for the Horten drawings, and; Dr. David Myhra and Dr. Karl Nickel for their support during this project. And with that he concluded the formal part of his presentation and opened the floor for questions.

The first question asked was when Reimar Horten designed the H Xc and Al stated it was in the early to mid 1950s, but there is no specific date on the drawings.

Bruce added a historical note here on large span, large aspect ratio aircraft. When he worked for Chance-Vought, he was moved to Grand Prairie, Texas where he discovered the Texas Soaring Association (TSA). On his first day there he ran into Dr.'s Raspert and Lippisch, and Lippisch gave a talk that night at a meeting of the aeronautical sciences people and covered the history of the Wasserkuppe.

One story Bruce remembered from the account was Lippisch's meeting with a guy by the name of DeJoiner who knew how to make good glue joints since he was a furniture maker. DeJoiner listened to Lippisch while at the Wasserkuppe and then the next year returned with an aircraft that had a larger span and higher aspect ratio than anyone had ever seen at that time. The engineers at the time told him it wouldn't hold and probably would break. So he pulled out about 50 reams of butcher paper to show them his calculations, but Lippisch couldn't make heads or tails of it and said they would have to proof load it to find out how much it could take. The proof load held and his techniques led to the development of bigger and higher aspect ratio sailplanes in the coming years (early 1920s).

Bruce commented that the H Xc looked like a very interesting approach to the concept of micro lift soaring like that being done with the Carbon Dragon. It can often stay up in the early morning hours by just meandering around like a vulture without really circling. So we need a ship with a very low sinking speed and good turning ability. Dr Paul MacCready had said back in 1959 that if he had a sailplane that sank at 1 fps he could fly anywhere at anytime during daylight hours and not worry about coming down. Bruce did an analysis on this concept and found that he had to get the ratio of the gross weight divided by the square of the wingspan down to about .08 to get 1 fps. The Carbon Dragon has about .165 and the new Light Hawk has about .145, but the Carbon Dragon has already been able to conduct micro lift soaring so the Light Hawk should be even better. He summarized that the H Xc could get down to about .10 with a light pilot, assuming the structure can be kept in the 90-100 lb area.

Ed Lockhart mentioned that he hadn't seen any type of diagonal bracing in the Horten designs and that this method provides much better torsional stiffness with a slight increase in weight. Al point out that the H Xb had some cross bracing in the elevon area, but he thought this might have been because the bell crank was at the inboard end and Horten may have been worried about its effectiveness. Al was intrigued by some of the talk by the Carbon Dragon guys where they are using wood laminated with carbon fiber and then making it into a D-tube structure. It looks normal but had good torsional stiffness.

Al commented he was amazed that Horten had come up with his designs based on the constraints of construction materials of the day. The fact that the Hortens actually flew the H VI was a significant event, since aspect ratios like this took years to come into their own. Even today, sailplanes with aspect ratios higher than the H VI and H Xc still use straight wings, and no one is doing it with a swept wing, which makes the job a lot harder.

Dominique Veillard asked what was the ratio between effective span and the physical span of the H Xc. Al said he hadn't done the calculations on that yet, but that David Lednicer did do it for the H IV. He found that the number was about .64, which is pretty bad. To some extent this number could be misleading since you are trying to compare a flying wing with a conventional aircraft where the tail surfaces are not considered in the aircraft's overall area. On a flying wing you still have the tail surface but it's just integrated into the wing and therefore calculated as part of the area. These types of comparisons may sell the flying wing short since it has other positive aspects that overcome some of these limitations. He loves the absolute simplicity of the flying wing and that everything you need is all in one package with no extra pieces tagging along for the ride. However, flying wings take a lot more engineering work to make the combined package work, where a conventional aircraft wing works well when you stick the tail out there to stabilize it.

Phil Burgers commented that with elevons we are trying to increase the lift of a flying wing, but in the H VI due to the sweep back the aeroelastic effects are going to decrease the lift gain. He thought it would be interesting to take the technology developed with the X-29 Forward Swept Wing project which actually directs where the torsional axis is in the structure, called aeroelastic tailoring, and apply it to something like the H VI. An H VI built with composite materials and improving the structure was one of the things Horten would have liked to see, but obviously it hasn't happened.

Gavin Slater noted that in the Dez George-Falvy analysis on the H IV from Mississippi State (MSU), it seemed the loading went negative at the tips under certain flight conditions. Al said it does become negative at very high lift coefficients, and in the case of the MSU results it appears to be due to aeroelasticity. David Lednicer had found distinct differences between the flight test data and computational data and, the only thing it could be attributed to was the aeroelastics. This has given them a very good model for what the aeroelastic deformations are in the H IV, but they don't know what they would be for something like the H Xc.

A comment was made about the small vertical surfaces on the H Xa. Al noted that they were used as stall fences because of some control surface problems. They do contribute a lot of drag but were necessary to improve the effectiveness of the elevons. Horten did get rid of them on the H Xb and the drawings of the H Xc also don't show any fences. Phil Burgers noted that the Urubu (H Xvc) that is being restored in Argentina was used as a prototype tester of these fences for eventual use in the I Ae 38 cargo plane so it would have a positive yawing moment.

Bob Chase noted that some of the early ultra light sailplane designers built in a lot of aileron differential and he wondered if Horten had used this technique in these designs. Al said Horten used zero since it would cause pitch trim problems. The differential they had existed between the amount of elevon deflection you got with pitch stick versus the amount you got with yaw stick and in the case of the H Xc it is 3:1.

Phil offered that Horten always used reflexed airfoils and that the one time he used a laminar airfoil (H IVb) there was a tragedy with it. So, he vowed to never fly in an airplane with a laminar airfoil and when the Argentinean Air Force would offer an Fokker F-27 to take him some place he would ask for a DC-3.

Apparently there are no drawings available of the H Xc except for what he had on his slide. So far he hasn't found anyone with drawings. He was asked what he would use for an airfoil and Al said he would use exactly what Horten did and, he would build it accurately to the 1954 design but probably with more modern materials (which Horten had wanted to see), although it would be interesting to try an replicate the exact wooden construction. [AHB: As mentioned earlier, Bill Moyes' H Xc is all-composite, but it weighs in at about 110 lbs.]

The question was asked whether the H Xc would operate at about the same Reynolds numbers as the H IV since the airfoils would be the same. Al noted that the Gottingen airfoils are appropriate since they only get about a 30% laminar run, but the pressure recovery is very benign on them and they behave very nicely at low Reynolds numbers. His analysis work included the Reynolds numbers from the H IV. When Al saw Horten's numbers of 30:1 L/D he immediately thought about the Flair 30 and SWIFT sailplanes and noted that Horten was coming up with the same performance almost 40 years earlier, so when he confirmed the performance numbers you can understand why he was pleased. The only drag component he hasn't been able to calculate is that of the pilot hanging out from part of the structure.

Asked if you would actually build one, Al was non-committal, however, he said a 1/5 scale model would give him about a 10' span for testing purposes. Asked if he would foot launch it he said he would probably prefer an auto tow. The next logical question was how about landing it? This is one of the questions he has considered since the lowest L/D number is about 20 and you can't slip it like a conventional aircraft since there isn't any rudder. He noted this could be a very entertaining project, Bruce mentioned using a drogue chute and Al said there could be small landing skid somewhat like the Flair 30.

And with a few chuckles about how the pilot would be positioned in the HXc and things like hitting sprinkler heads in alfalfa fields on out landings, Al brought this program to a close.

[AHB: In discussions with Bill Moyes, I understand the Moyes design has adverse yaw, so much so that Bill is considering some sort of vertical surfaces. However, while Bill appears to have the correct twist, he has enlarged the elevons inboard, which may be the source of the adverse yaw. Bill has flown the H Xc to 2000 ft agl, usually launching on auto tow, but has foot launched it though it is awkward, and plans to continue work on the design. Bill reports performance of about 30:1 L/D and a minimum sink of 120 fpm.]