FLYING WING GEOMETRY

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In 1910, the German aircraft builder Hugo Junkers filed Patent #253 788, which predicted that the flying wing would be the final solution to aircraft development. This document known as the "Volume-patent" suggested that the wings should provide space for not only the engines and their fuel, but also for payload and crew!

Aircraft of that time were externally braced mono or bi-planes with their fuel tanks suspended free in the airflow. This enabled the pilot to detect leaks quickly, and the escaping fuel would be carried away with the wind, thus minimizing fire hazards. The pioneering developments by Junkers in the period from 1915 to 1929 produced an aircraft with a cantilever wing where the engines, fuel tanks and even some of the passengers were accommodated within the wing structure. (G-38). This aircraft still incorporated a fuselage and tail surfaces, since the necessary stability and controllability of the wing by itself was not yet obtainable. A 100-ton pure flying wing, the JU 1000, designed in 1930, was unfortunately

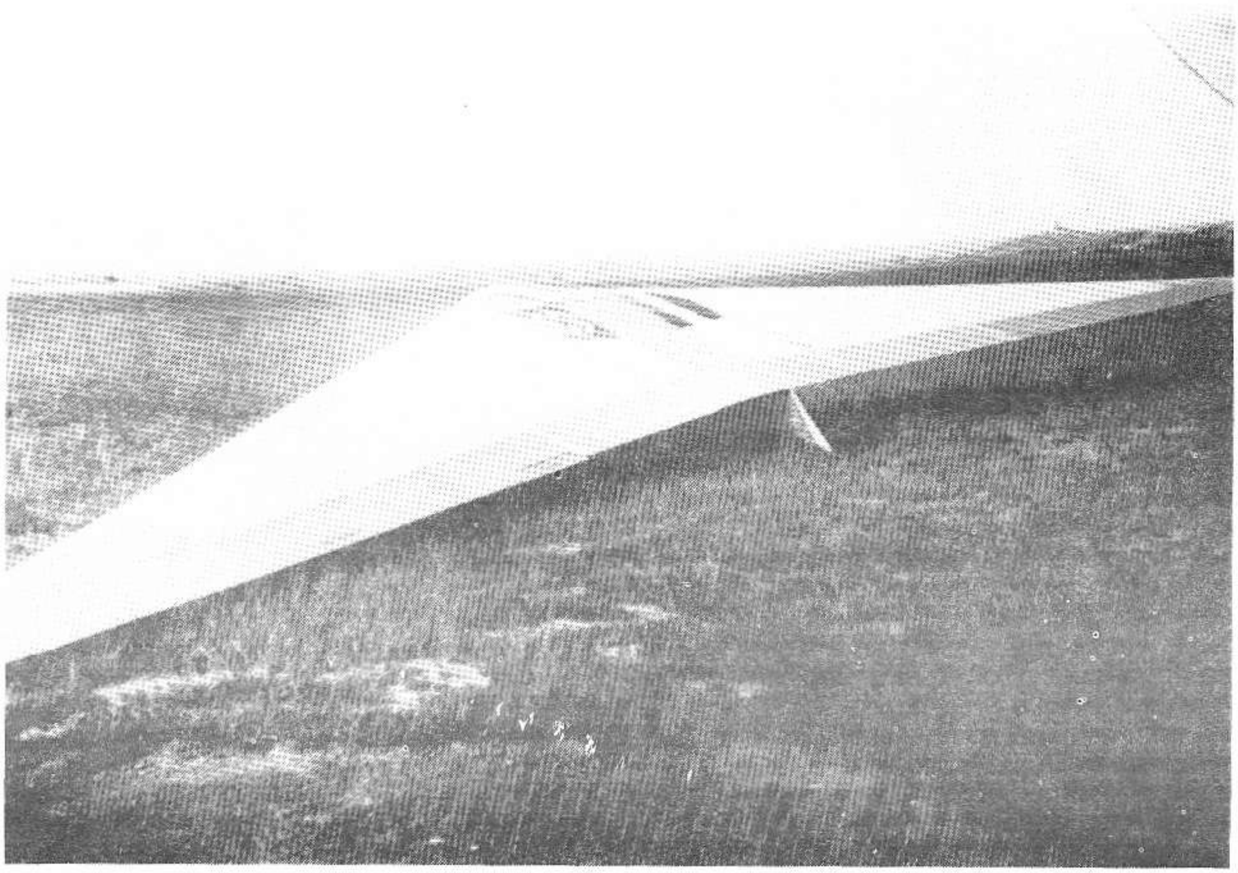

Photo 1. The Ho II

never built.

When a body is enlarged, without changing its basic shape, the surface grows in the second power of the increase in size, and the volume in the third power. Aircraft size is commonly determined by their maximum take-off weight. By constant wing loading, this will also determine the wing area. The relationship between wing volume and wing area grows in proportion to the wing size, so that a large aircraft can easily accommodate non-lifting components and payload within the wing. In the case of smaller aircraft, one must try to find a wing shape that provides adequate room within its structure while the size of the machine is kept within reason. Once the desired airfoil and wing area has been determined, the volume can only be changed by varying the wing taper towards the tip.

In a rectangular halfwing, the volume is equal to the rib surface multiplied by the halfspan. In a triangular shaped wing with the same area, the tip chord is zero, and correspondingly, the root chord is doubled. This quadruples the base surface of an imaginary cone, which has a specific volume of 1,33. - hence the triangular halfwing contains 33% more volume than a rectangular wing of the same airfoil, span and area!

A tapered wing's volume will lie somewhere between these extremes, and can be calculated as a cut-off cone.

If now the wing is swept back to eliminate tail surfaces, it is important that the center of gravity remains very close to the center of pressure (lift). This is not as critical with conventional aircraft, where any pitch-moment can be controlled with the elevator. A swept wing should have its center of pressure at $Y = 1/3$ on the halfspan, to obtain the desired bell shaped lift distribution curve (Soaring, June, 1981, page 40) and at 25% of the chord.

The useable space within the wing must be planned so that its center initially corresponds with the center of pressure. Only then will the center of gravity remain in its proper place regardless of the amount of fuel, cargo, etc. that is put aboard.

The useful space within a rectangular wing would be limited to the inboard 70% or less, as indicated by Fig. 1, curve A. The useful space within a tapered wing would be much higher, as indicated by curve B. In fact, it would be even higher, since it is usually possible to load the full span volume, rather than just the inboard 70%.

The difference would be still larger if the rectangular wing utilized a laminar airfoil where the maximum thickness lies at about 40% of chord. To keep the center of gravity at the desired 25% location, the available space could only be partially utilized.

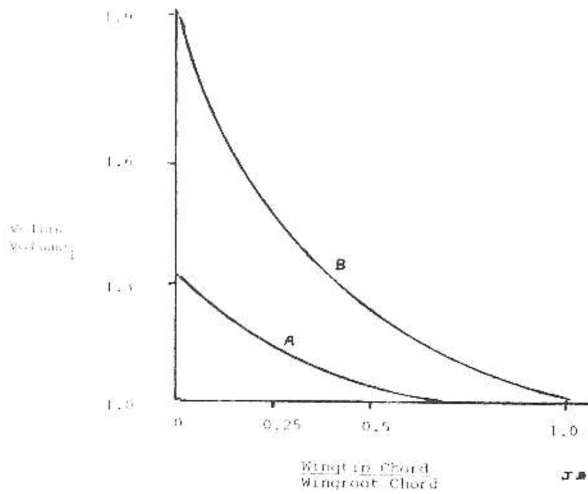

Figure 1.

One may ask if these considerations have any value for the designer of small aircraft and sailplanes, where available space inside the wing is of little or no importance~!

Consider Kelley's formula for calculation of wing weight, which shows that the spar weight diminishes with increased wing root thickness. The bending forces on the spar is also reduced by increasing the wings taper, thus both spar caps and skin can be made lighter. The relationship between volume and torsion stiffness is also obvious, a large circumference at the root provides better resistance to the twisting moment, thus improved stiffness. For these reasons, a steeply tapered wing becomes an important design consideration even for small aircraft.

How far can one go with the tapering of a flying wing glider? In consideration of the prone positioned pilot (Soaring, August, 1980, page 22) the taper should be as steep as possible to provide maximum room for the pilot inside the wing root. The theoretically ideal triangular wing with pointed tip can not be used for three practical reasons.

1. Construction; it is impossible to accommodate elevons and drag rudders at their ideal location from Y=0.95 outward, due to insufficient wing chord.

2. Static loads; the tip must be able to withstand certain minimum ground handling loads, generally 50 kg in any direction. The Ho IV had a narrow 30 cm chord at the tip, and handling loads were limited to 30 kg, since the slim metal tip containing both elevon and drag rudders would not sustain higher stress. Inflight loads were well below this value. On the Ho VI with a 20 cm tip chord, only 20 kg handling loads were allowed. These slim 2.8 m long metal tips were masterpieces of craftsmanship. During flight, the flexing of the wing was considerable, and the bending of the tip as it touched the ground was of great concern. Despite the fact that no failure occured, 20 kg handling resistance at the tip should be considered insufficient. With the normal 100% safety factor, 30/60 kg is the minimum recommended tip handling load resistance.

3. Aerodynamic consideration; the lift distribution (Soaring, June, 1981, page 40) is not the concern here, but rather the Reynolds number of the airfoil which must exceed a minimum value.

This may at first appear to be a paradox! At all re-numbers, whether laminar or turbulent, or a combination of both, as long as the boundary layer changes at the same point on the chord, the tapered wing will have less friction-drag than the rectangular. The taper rate limit as governed by the re-number, appears to be around 2,000,000 with a turbulent boundary layer and a 20 cm tip chord, and 5,000,000 with a laminar airfoil and around 50 cm chord.

Thus a sailplane with a tip chord as small as 20 cm must use a conventional airfoil like the NACA four digit group, to avoid flow separation with its associated large drag increase.

The behavior of a laminar airfoil on a swept wing presents further problems. The spanwise bending of the flow induced by the sweep back changes the pressure gradient of airfoils designed for straight wings, however the total area of laminar flow is not changed, and performance is not affected.

The sweep back deflects the boundary layer towards the tip, and warrants further research, since it affects stability. If the aircraft skids, one wing attains more sweep back than the other in relation to the airflow, and different boundary layer deflection occurs on the two wings. This deflection should not be confused with the separation that occurs when approaching a stall. The asymmetric spanwise flow that occurs in a skid tends to increase drag on the lagging wing, creating instability around the yaw axis.

Directional stability on a wing without vertical stabilizer is generally low. With 100% laminar flow, the center of friction drag is located at 20% of chord, thus 5% ahead of the center of pressure and the C.G. The natural consequence is yaw instability.

With a turbulent boundary layer, the center of drag moves aft to about 40% of chord. Now with the center of drag 15% behind the CG, directional stability is attained. Surprisingly, if a combined laminar/turbulent airflow is provided, with the changeover at 50%, the center of drag moves all the way back to 60%^ of chord. Since this is the typical flow pattern of the laminar airfoil, a flying wing so equipped would have superior directional stability. This stability remains positive during large skids, but at smaller skid angles it may become negative, due to the asymmetrical deflection discussed previously. This may cause "swimming," a continuous light oscillation around the yaw axis.

Windtunnel tests in Cordoba revealed that by notching the trailing edge in a sawtooth fashion to a depth of 10% of chord, one was able to eliminate the deflection and obtain a chordwise flow. Also increasing the amount of washout from a given point on the wing trailing edge had the same effect. During up elevon deflection a channel was formed, through which the boundary layer was bled off. A fence near the leading edge had greater effect than channels or notches at the trailing edge, and it appeared from the wind tunnel tests that the leading edge should be stepped forward with a chord increase of about 10% at Y=0.80. This would leave the trailing

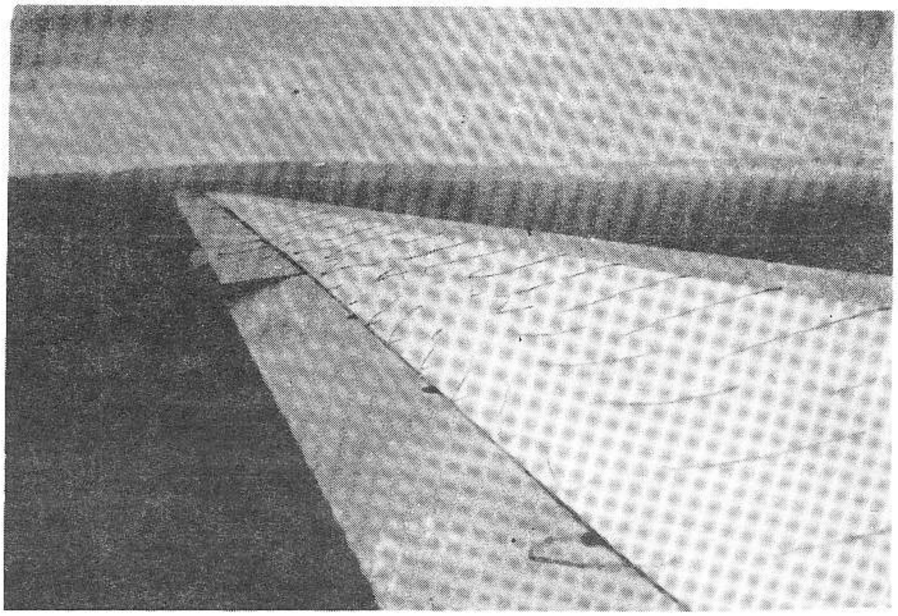

Photo 2. Wool tufts on top of a Ho VX wing shows how the boundary layer is deflected towards the tip but is bled off at the notch created by the "up" elevon. Normal chordwise flow exists outboard of the notch.

edge undisturbed, as the washout is obtained by lowering the leading edge. Shaping and orunding of the step area with modelling clay resulted in a smoother pressure curve, as well as improved yaw-stability. The local interruption of the lateral pressure gradient caused the boundary layer to flow towards the rear without disturbance at the wing tip.

It appears then that one can obtain full directional stability, even during small skids, by providing the swept wing with a laminar airfoil between the root and the leading edge step at Y=0.7 - Y=0.8, and the remainder of the wing with a conventional airfoil with a low re-number, and also proper fairing at the leading edge step.

It is regrettable that this theory has not yet been proven, since no suitable machine has been built or flown for the last 20 years. As new areas of knowledge opens up, it is very important that each new discovery be confirmed by practical tests.