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IMPROVEMENT OF HANG GLIDER PERFORMANCE BY USE OF ULTRALIGHT ELASTIC WING

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SUMMARY

The problem of the lateral controllability of the hang glider by the pilot's weight shift is considered. The influence of the span and the torsional elasticity of the wing is determined. It is stated that an ultralight elastic wing of a new kind developed by the author is most suitable for good control. The wing also has other advantageous properties.

INTRODUCTION

The main problem affecting the development of ultralight gliding is the decrease of the control effectiveness of the pilot's weight shift when the wing span increases. However, increasing the span and consequently the aspect ratio is the only way to improve the lift-drag ratio (L/D).

The important effect of the aspect ratio on the L/D for a definite type of external skeleton of the ultralight wing can be shown as indicated in figure 1 (ref. 1). Areas A, B, and C indicate the causes of the diminishing of L/D. Figure 1 shows that the induced drag A is the main price of lift production and can be diminished mainly by increasing span. Changing the unadvantageous triangular wing planform of the early flexible wings improves it to some degree and the application of final winglets makes it possible to improve it even more. Area B on figure 1 illustrates the influence of the wing profile effectiveness on the hang glider L/D, which is not very sensitive to profile shape above an aspect ratio of 5. Finally area C, the skeleton drag, constitutes the main field of the designer's activity. It is very interesting that for all wings with external skeleton (with external spars and struts (a), with external spars and cables (b), and with external cables only (c)), an optimum aspect ratio always exists. The maximum of L/D can be explained by the considerable drag increase. which for some aspect ratios exceeds the decrease of induced drag.

It has been shown in figure 1 also that the optimum aspect ratio can be a considerable one for ultralight wings. It enhances application of wings with enlarged spans. A difficulty with higher aspect ratios is that the lateral control of simple hang gliders by the pilot's body shift only is worsened.

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ANALYSIS OF LATERAL CONTROL

To analyze this challenging problem, the time to bank the wing 60° was calculated (from +30° to -30°) as shown in figure 2. First a completely stiff wing was considered, for which the inertia forces were neglected. Next a wing completely elastic in torsion was considered, for which all the lateral aerodynamic moments were neglected. It was a soft wing, longitudinally stabilized aerodynamically, with the roll moment of inertia forces only considered. In the first case the responses on the control force moment were aerodynamic forces and in the second case solely the inertia forces. These two cases can be regarded as boundary limits on the roll rates of all real wings of hang gliders.

For the first case the following relation was found:

$$t = \frac{dC_L}{d\alpha} \frac{\psi \ell^2 L}{16 r W_1 v C_L} \qquad \text{(sec)} \qquad (1)$$

where

C_L	lift coefficient
α	angle of incidence, deg
ψ	bank angle in figure 2, deg
ℓ	wing span, m
L	lift force ($L = W_1 + W_2$), daN
W_1	pilot weight, daN
W_2	glider weight, daN
r	mean body shift of the pilot, m
v	flight speed, m/sec
t	time to bank from -30° to $+30^\circ$, sec

and for the second case:

$$t = \sqrt{\frac{\psi m \ell^2 \pi}{8 r W_1 180}} \qquad \text{(sec)} \qquad (2)$$

where m is the glider mass assumed to be uniformly distributed spanwise. Furthermore it was assumed that this mass grows linear as a function of the span according to the formula,

$$m = \frac{W_2}{g} \frac{\ell}{\ell^*} \qquad (3)$$

where

g Earth's acceleration, m/sec^2

ℓ^* wing span, m, of hang glider weighing W_2, daN

For the calculated practical examples the same values were assumed: $W_1 = 75$ daN, $W_2 = 25$ daN, $r = 0,75$ m, $\psi = 60^o$ and furthermore $dC_L/d\alpha = 0,06$, $v = 8$ m/sec, $C_L = 0,7$, $\ell^* = 12$ m.

The results of the calculation are shown in figure 3. They concern two ideal boundary cases 1 and 5 and three known types of hang gliders 2, 3, and 4. Particular curves concern the following types of ultralight wings:

1 - stiff wing

2 - Rogallo wing with flexible canopy characterized by limited washout of the wing

3 - sailwing or Rogallo hybrid wing of increased washout

4 - sailwing or hybrid Rogallo wing with automatically changing sailbillow and washout

5 - elastic wing of maximum abritrary washout

In figure 3, three ranges of bank time for the mean body shift $r = 0,75$ m of the pilot weighing 75 daN are shown. The first range of t from 0 to 2 sec is the safe range of good manoeuvrability of the hang glider. It corresponds to practical observations of gliders and BCAR, section K, for the light airplanes (ref. 2). The second range of $t = 2$ to 4 sec is, under some weather conditions, an acceptable range of sufficient manoeuvrability. The third range, t greater than 4 sec, is dangerous for hang gliders and can be accepted only in particular cases as for man-powered airplanes at wind speed less than 2 m/sec.

In figure 3, the estimated bank time of the historical Lilienthal's gliders of 7 m span is indicated by a circle. They were controlled less effectively than contemporary hang gliders. Their bank times of 7 sec were within an unsafe range. That explains the half-century of stagnation in development of that form of gliding. Its revival was possible when the value of $r = 0,2$ m was increased to nearly 0,7 m when the harness for the pilot was invented.

The bank times indicated in figure 3 concern a considerably low flight speed $v = 8$ m/sec, and it is known that the aerodynamic control effectiveness diminishes with the air speed. However this bad property does not occur in the case of hang gliders controlled by weight shift, as was expressed by formulas (1) and (2). This problem can be presented clearly by taking into account that for the formula (1) and for the weight control the relation $C_L \sim 1/v^2$ is valid. Next for the formula (2) and aerodynamic control (when the inertia forces are the only response on the control force), the control moment $rW_1 \sim rv^2$ applies. Then we obtain relations shown in figure 4. This table shows very unadvantageous characteristics ($t \sim 1/v$) of the aerodynamic control for low speed flying devices operating near stall and being intended to operate like a parachute. On the other hand the weight control has suitable characteristics at low speeds and improves when the speed diminishes ($t \sim v$). It even can be independent of the speed ($t \neq f(v)$) in the case of the torsionally very elastic wing under consideration. Of course, this relationship remains valid if the wing is stable during stall or, in other words, if the separation is symmetrical.

DEVELOPMENT OF Z-77 HANG GLIDER

The development of an ultralight wing of this kind was very troublesome and took the author about 10 years. Initially the work concerned a wing with a cable leading edge (ref. 3) stretched by means of a pulley and a spring or rubber rope expanded along the spar tube of the skeleton. These experiments showed advantageous features of the ultralight foldable wing with the canopy fixed at one point of the tip to the wing spar and having a hinged end rib. The rib hinging on the cable or on the tube can change the angle of attack of the wing lip. The torsional elasticity allows self-adjustment of the wing to the flight conditions and good lateral control by weight shift only. Therefore it was decided to design the experimental hang glider Z-77 with a considerable span of 12 m, a rectangular wing planform, and a single central vertical stabilizer (ref. 4).

This simple flying plank arrangement was chosen as a result of the author's own wide experiments and of an analysis of positive swept flying wings. Its general properties are unstable stall for larger aspect ratios and bad dive recovery of flexible wings with soft tips and no profiled central rib. These properties create limits of a narrow speed range due to unsafe characteristics in turbulent wind conditions. It was found that the greatest chance of eliminating these undesirable properties is by application of an arrangement with slightly negative sweep of the wing. It is just the arrangement of the hang glider with reasonable application of an elastic wing characterized by one point connection of the sail tips to the skeleton, and by torsional elasticity of the wing plane.

The hang glider Z-77 was designed according to the general rule, "first safety and later the performance." The second more sophisticated rule was "do not counteract the deformation but organize and exploit it for safety and performance purposes." According to this second rule the wing bends and twists considerably around the leading edge which acts as a spanwise hinge.

The first variant of Z-77 tested in 1977 had the cable leading edge and external spar (fig. 5). Its stability and control was excellent and the only drawback was tearing of the canopy as result of contact with the wires, when the glider was standing windward nose down on the ground. This drawback was so significant that after 15 minutes of wind pressing on the wing the sail had to be repaired.

This defect led to a modification of the construction by inserting a spar tube into the sail. Furthermore the spar was supported by only three wires so situated that the sail would not touch the wire under any conditions. In the second variant of Z-77 a double membrane airfoil (dark in the pictures) for 50% of the chord was used with duraluminium sheet profiles similar to those in the first variant.

This second variant of Z-77 (fig. 6) had an extraordinarily wide speed range and a very soft and stable stall. The glider was generally fast, considering the area of 20 m^2. This was the result of relatively flat self-stable profiles of the same kind as those used in single membrane version. The glider was very stable in turbulent winds and its longitudinal and lateral control was good. It participated in hang glider competition in the Zakopane-Tatra mountains in 1978. After numerous flights the next modification of the wing (fig. 7) was undertaken in order to improve its L/D above 10 which is possible for the structural arrangement used and an aspect ratio of 7.

For this purpose, new more effective special profiles were developed and the planform of the wing was slightly changed. During very many test flights, sometimes of 10 minutes duration, the glider demonstrated a very low minimum speed of 20 km/hr and a considerable lift coefficient (nearly 2). Determination of maximum speed was more difficult, but speeds of 80 km/hr were reached without any problem.

The modifications and the test flights are continuing. The main task is to improve the L/D to the possible nearly 15 while maintaining the hang glider's safety by good stability and controllability. The safety achieved is due to such properties as

- possibility of stable and controllable stall and parachuting from any altitude

- impossibility of slipping the wing and asymmetrical stall

- impossibility of spin

- controllable diving and easy recovery from dive

- very wide speed range and its safe boundaries (very important under strong wind turbulent conditions)

- possibility of immediate transition from dive to parachuting on the same straight line trajectory, losing only a dozen meters of altitude

The last of these properties is an extraordinary one and deserves some words. It was known that for the definite geometry of the glider there is one speed polar for the steady flight. But the spring wing of Z-77 is very elastic in torsion and therefore its velocity polar is the envelope of an infinite number of polars for different twist angles of the wing. This is shown in figure 8 which explains the reasons for the wide speed range of Z-77. On the resulting polar, for the great range of the trajectory inclination angle, the two points A and B can be found for which the glide angle is the same. However, the speeds of diving and parachuting differ. For the hang glider of fixed geometry, considerable sweep or conventional horizontal tail stabilizer, a quick move from the state A to B on the straight line trajectory AB is practically impossible and occurs during pull up manoeuvre or a slack stall along the curve AB. Large span flexible wings with considerable leading edge sweep and a negligible torsional elasticity of the sail with the unelastic flexible canopy stressed between the keel and leading edge tubes behave similarly.

A completely different situation occurs when the hang glider has an elastic wing, has no horizontal tail surface or sweep, and has a low moment of inertia in pitch. Then a sudden transition from point A to B on the straight line trajectory is possible at a sufficiently large and fast increase of the incidence angle. Of course a moderate but not too slow increase of incidence angle normally results in dynamic climbing. At a slow increase of incidence angle the glider mushes according to the curve AB.

The dynamic stall and the manoeuvre of landing in a difficult situation as described and explained above is generally simple. However, technically the problem is more complicated because the torsional elasticity and the time of manoeuvre have to be suitable. These factors cause the deviation of the real trajectory from the straight line AB. Briefly, the control forces and manoeuvre time associated with insufficient elasticity exceed the physical capabilities of the pilot. On the other hand too much elasticity hinders dynamic climbing and causes pancaking of the glider. These problems and others are the subject of further research and tests of Z-77 (which has made about 400 flights to date). Moreover, Z-77 actually enables short and precise landings behind obstacles using the whole wing area as a powerful aerodynamic brake.

The actual data of Z-77 (fig. 9) are

Weight, 25 daN
Span, 12 m
Length, 5.5 m
Area, 19 m^2
Speed range, 20 to 90 km/hr
Lift-to-drag ratio, 12
Profiles, special, self-stable
Maximum chord, 1.8 m
Minimum chord, 1.5 m

The hang glider Z-77, which was not described here technically, includes some essential patented improvements. The glider based on the application of the ultralight elastic wing is capable of performing the dynamic stall landing process attainable until now practically only by birds.

The ultralight elastic wing can be used for the practical investigation of the new unconventional landing technique, and for the development of the high performance deployable flying devices (for example, hang gliders of the class 2 of FAI-CIVL regulation). This wing can be based on the application of the cable or tube leading edge arrangement. Its actual and possible future lift-drag ratio is compared in figure 10 with that of other ultralight wing types. Because of the possibility of high L/D, it is very suitable for oscillating wing propulsion of hang gliders (ref. 5) and has been practically proved and tried by the author in 1976-1977 by use of an elastic pilot harness and foot straps.

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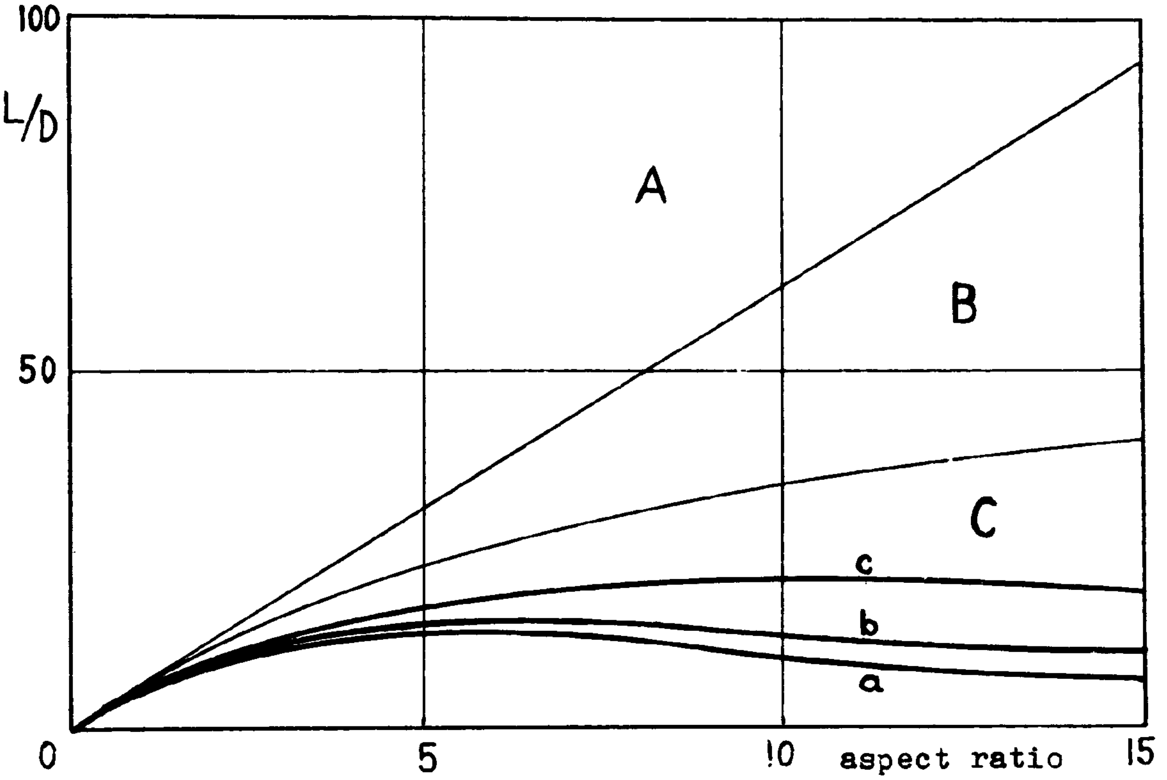

Figure 1.- Influence of the induced drag (area A), profile drag (area B), and skeleton drag (area C) on the lift/drag of the ultralight wing with external skeleton having spars and struts (a), spars and cables (b), and only cables (c).

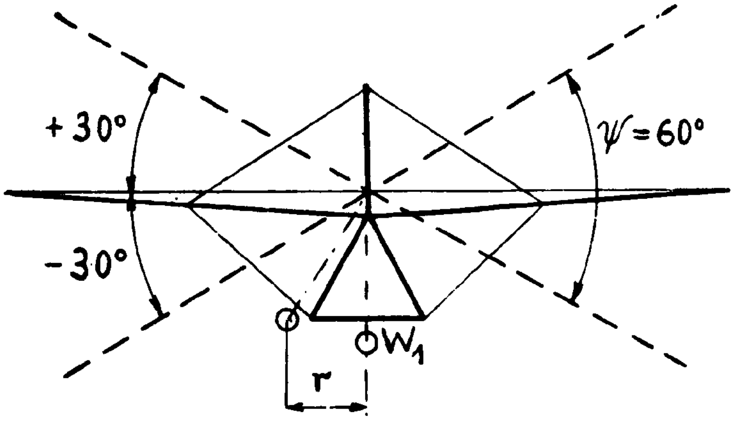

Figure 2.- Considered bank angles of the hang glider.

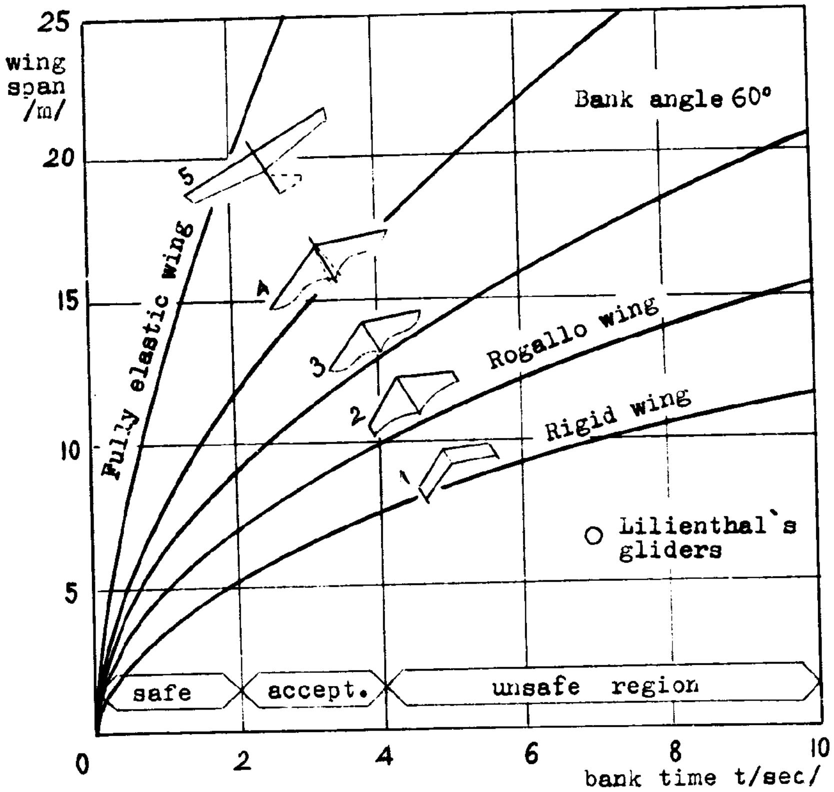

Figure 3.- The bank times t for the hang gliders controlled by mean body shift r = 0,75 m of the pilot weighing W_2 = 75 daN as a function of wing span ℓ.

		Control type	
		aerodynamic	weight shift
Wing type	rigid	$t \sim \frac{1}{v}$	$t \sim v$
	elastic	$t \sim \frac{1}{v}$	$t \neq f/v/$

Figure 4.- Correlation of the bank time t with flight speed v.

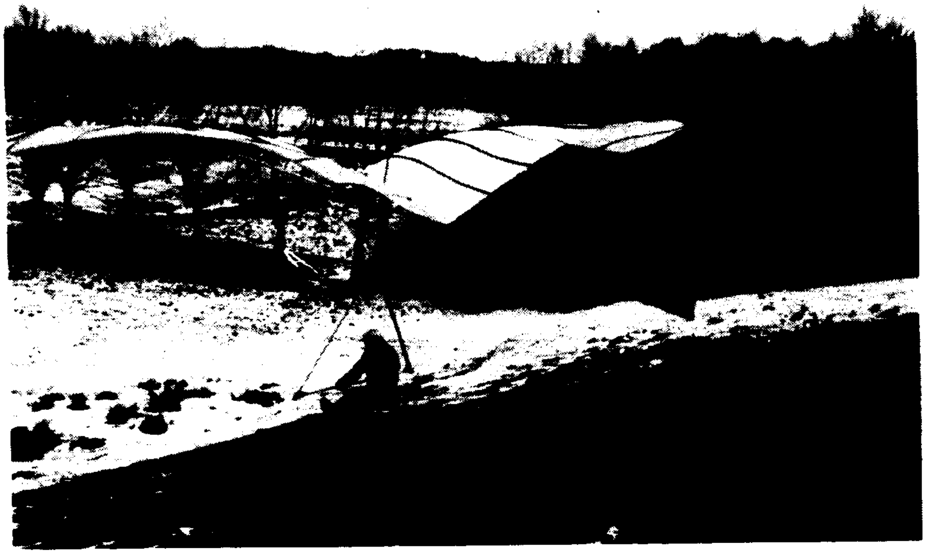

Figure 5.- Experimental hang glider Z-77 (first variant) with cable leading edge elastic wing.

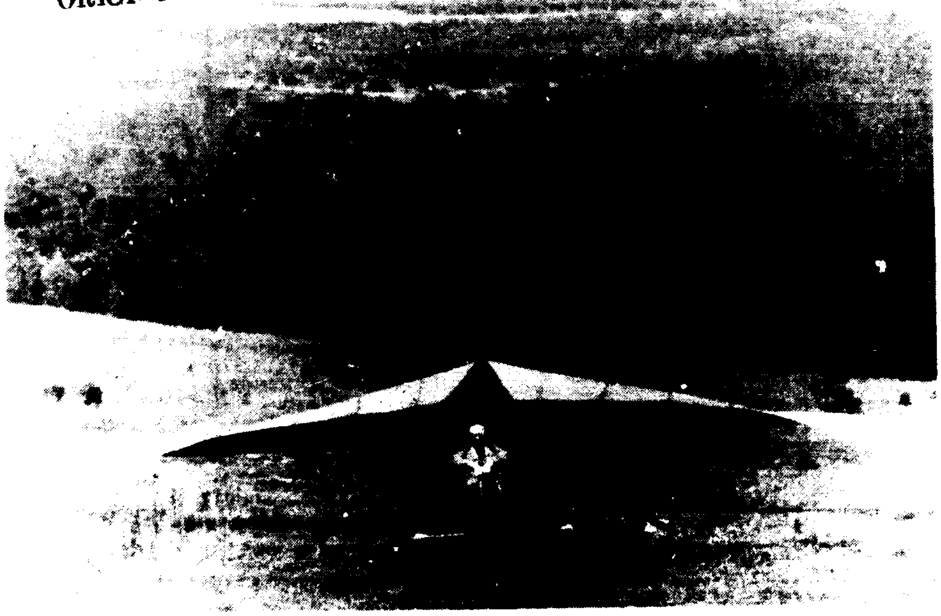

Figure 6.- Tube leading edge hang glider Z-77 (second variant) demonstrates the considerable range of the wing twist.

Figure 7.- Tube leading edge hang glider Z-77 (third variant) in flight.

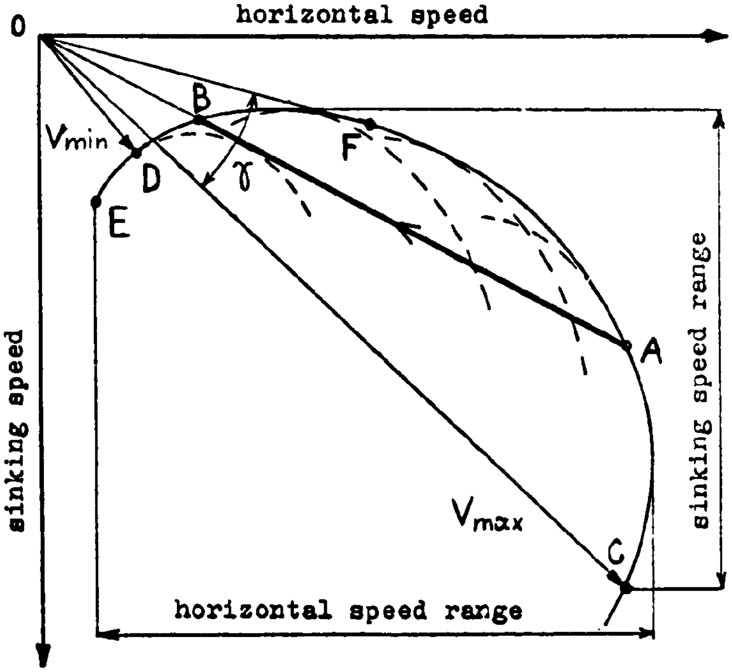

Figure 8.- Velocity polar of elastic wing hang glider. A,B - the points of polar curve for diving and parachuting on the same flight path inclination; C - the point of maximum speed; D - the point of minimum speed; E - the point of the maximum vertical parachuting; F - the point of maximum L/D; γ - the range of the flight path inclination angles for dynamic parachuting; $v_{max}-v_{min}$ - the range of flight speed. The velocity polars for various wing twist are shown by dashed lines.

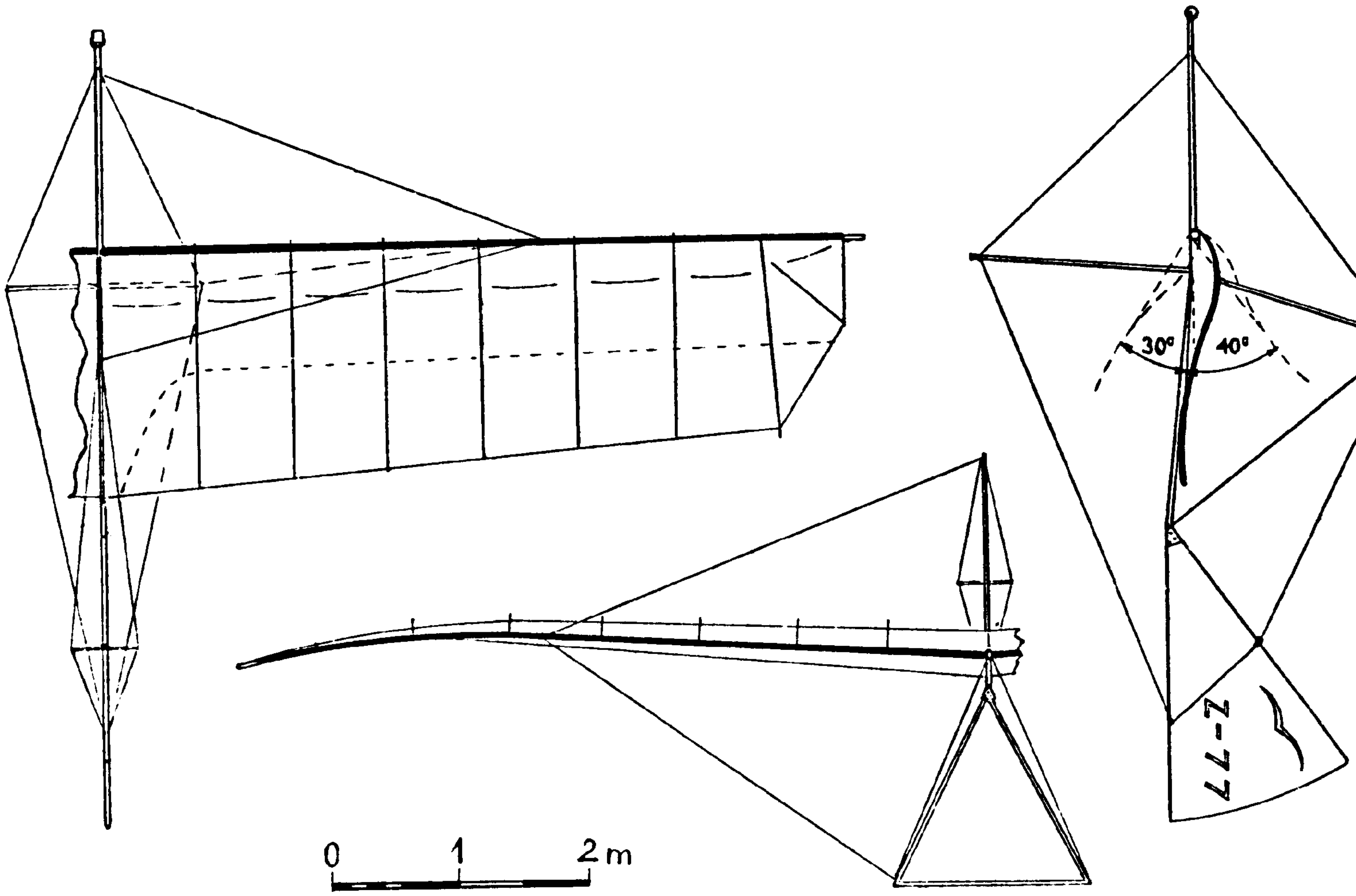

Figure 9.- Sketch of the third variant of Z-77.

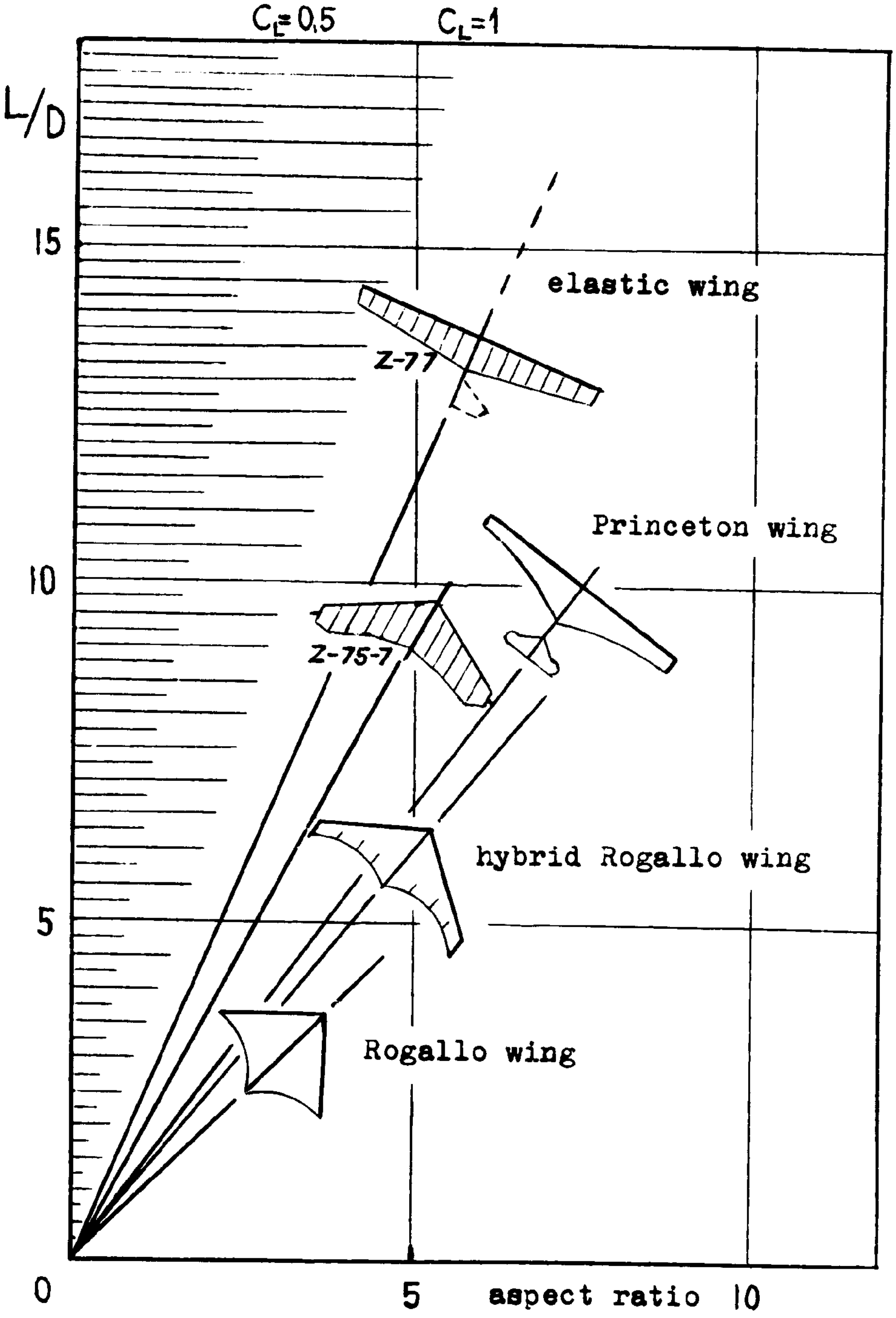

Figure 10.- Lift/drag as a function of aspect ratio for various ultralight wings.