maximum deviation of the trajectory of the operator and the glider from the rectilinear trajectory of the centre of gravity of the system as a whole and, more accurately speaking, the oscillation node, is equal to the amplitude of deflection of the suspension springs from the equilibrium position. It depends on the ratio of the weight of the operator W_1, to the weight of the wing W_2 so that

$$\frac{h_2}{h_1} = \frac{W_1}{W_2} \qquad /10/$$

This means that, if the weight of the wing decreases, its amplitude increases and the amplitude of the pilot decreases.

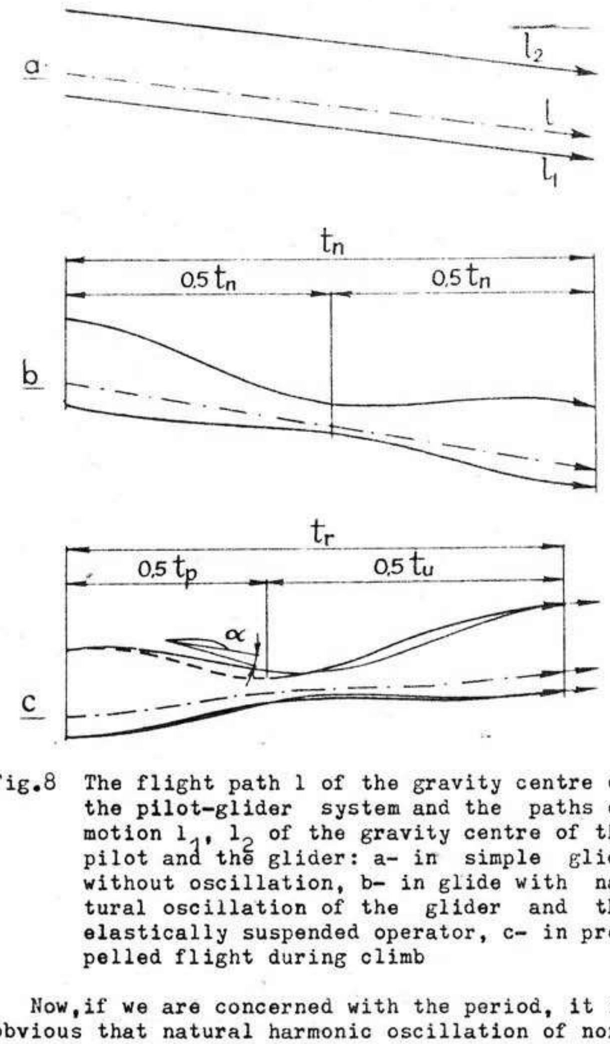

Fig.8 The flight path l of the gravity centre of the pilot-glider system and the paths of motion l_1, l_2 of the gravity centre of the pilot and the glider: a- in simple glide without oscillation, b- in glide with natural oscillation of the glider and the elastically suspended operator, c- in propelled flight during climb

Now, if we are concerned with the period, it is obvious that natural harmonic oscillation of non-propelled wing has equal half-periods of $0.5\ t_n$. If energy is supplied by appropriate repeated action of muscles of the legs, the trajectories take for climb a form as shown in Fig.8c. The dotted line marks the segment of the wing path corresponding to the propelling stroke. Thin lines show, for comparison, the trajectories under conditions of natural oscillation.

During the working stroke the pitch angle of the glider must be decreased by precise control in order to preserve the optimum incidence angle of the wing. This control must be effected by the hands of the pilot who acts on the control frame 6, Fig.5. The control of propulsion is simultaneous with that of altitude and consists in displacing the control frame forwards thus increasing the pitch angle and back to decrease that angle. Good longitudinal self-stability will enable automatization of these operations, which will facilitate piloting.

V. Dynamic of Wing Propulsion

The most essential for wing propulsion is that fragment of the cycle /the propulsion stroke/, in which the pilot exerts a force on the trapeze, thus accelerating the wing downwards in a direction transverse to the flight trajectory. This action must be done during the mutual approach of the two masses, those of the operator and the glider which, except of the particular case of F_ζ = const. already described, produces usually increased transient dynamic load on the wing which will operate, at an increased angle of incidence α.

Fig.9a explains that this will result in an increased vertical component of the aerodynamic force $F_\zeta > W$ and an increased resultant F_a. Together with the forward inclination of the vector F_a this will produce a thrust component F_ξ. With more active control the force F_a will be smaller but its forward inclination will be greater. On the other hand, with reticent control, no control at all, or negative control, the force F_a will increase considerably /until stalling occurs/ with backward inclination, thus giving even a negative component, which increases the drag. Then, the propulsion power will be used for braking the flight, which may be done during landing, for instance.

The variability of the force F_a during a simple cycle in the particular case of F_ζ - /iT+W_2/= = Z is represented in Fig.9b. The force F_a, which is shown, is the transient total aerodynamic force acting on the wing. Its vertical component F_ζ is equilibrated by the reaction R composed of the impulse force of propulsion Z, the tension of the springs iT produced by the mass forces of the weight of the operator W_1, and the weight of the glider W_2. The variation of the force Z is represented in Fig.9b by a dotted line and the direction of the force F_a is marked by inclined arrows, which means that its value should be read in the variable oblique coordinates F_a, ξ. It is observed that, in the control method considered, the load factor of the wing passes through a value of n = 1 at the middle point of the climbing phase, at which the tension force of the springs is equal to the weight of the pilot W_1. A maximum n = 2.5, which is considerable, will occur in the middle of the phase of wing acceleration during the propelling stroke.

The diagram of Fig.9b enables us to determine the variability of the horizontal thrust $+F_\xi$ and the drag $-F_\xi$ for the entire cycle by determining the component of the force F_a in the direction of the ξ axis. As a result we obtain the diagram in Fig.9c, which shows that positive values of F_ξ representing the thrust occur during a small part of the cycle and the condition of horizontal flight is

$$\int_0^{il} F_\xi \, d\xi = 0 \qquad /11/$$

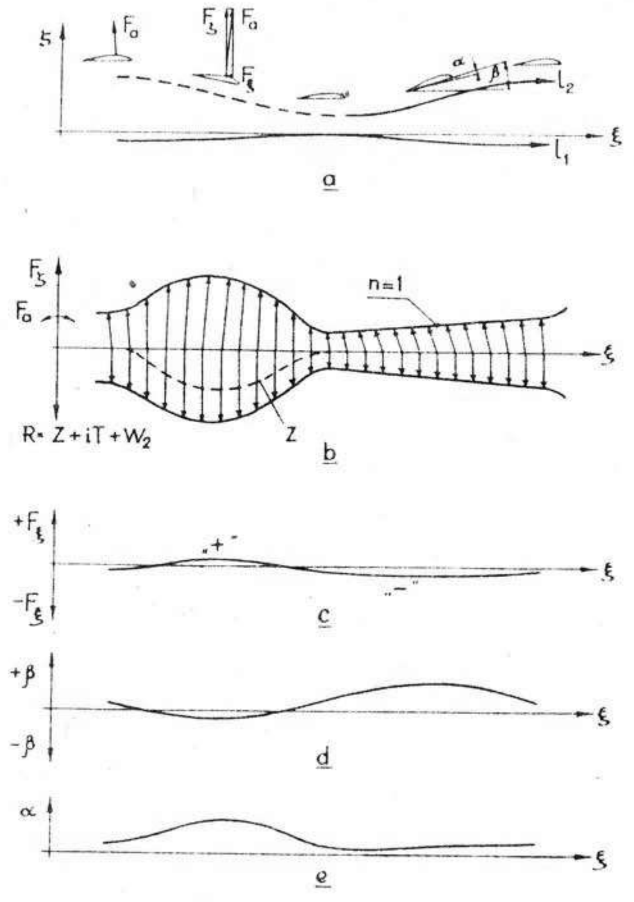

Fig.9 Variation of the main parameters per one propulsion cycle, if the propulsion force Z is equilibrated by an increase in the vertical aerodynamic force F_ζ: a- the trajectory and the position of the wing for several phases of motion, b- variation of the magnitude and the direction of the forces acting on the pilot-glider system, c- variation of the thrust and the drag, d- variation of the pitch angle of the glider, e- variation of the angle of incidence of the wings

The variation of the angle β required in this case **which determines** the way of wing control is illustrated in Fig.9a and, in Fig.9d. The variation of the incidence angle is represented in Fig.9e. The latter diagram shows the disadvantageous variability range, which is considerable, of the incidence angle of the wing, if the control is realized according to the principle F_ζ-/iT+W_2/= Z that is with immediate equilibration of the force Z by an increased force F_ζ.

Fig.10 represents, for comparison, the same quantities as in Fig.9 for another particular control method, with constant force $F_\zeta > iT_{max} + W_2$. Comparison shows that this way of control will be much more advantageous from the point of view of propulsion efficiency, owing to the possibility of the wing being operated at a practically constant optimum incidence angle α and because the force F_ζ is constant and the force F_a is almost constant. In addition, the small constant load factor n is also of advantage. The latter feature is very important for the practice, because it enables the use of a lighter wing with the same safety margin of the structure.

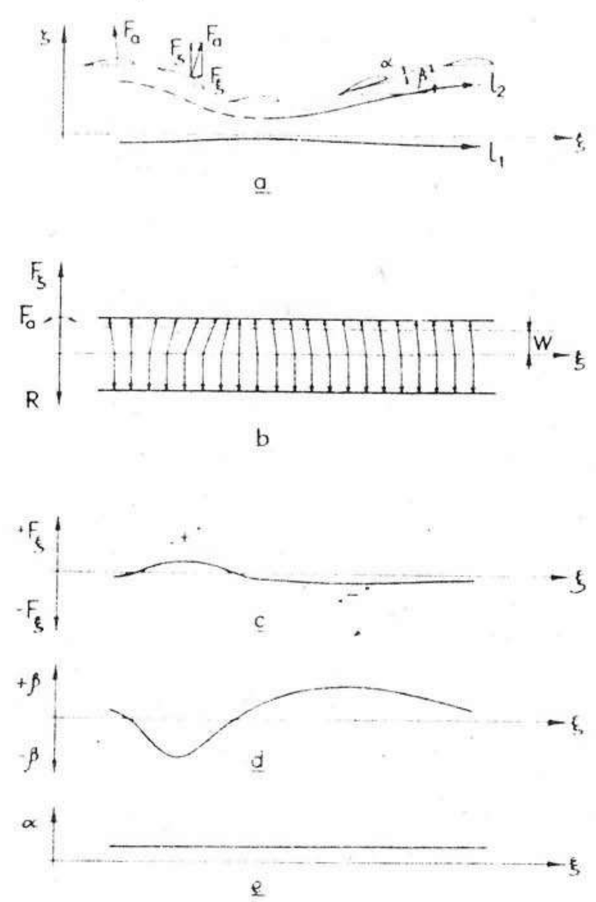

Fig.10 Variation of the main parameters for one propulsion cycle in the case of constant vertical aerodynamic force F_ζ. Notation as in Fig.9

Confrontation of Figs.9d and 10d shows that for the realization of the propulsion type with F_ζ = const. which is more advantageous, wing control with a wider variability range of the pitch angle β of the glider is necessary. This cyclic control must be accompanied by flight control in the remaining two planes of motion without interrupting the propulsion during turns or other manoeuvres. This is facilitated by the fact that the flight and its propulsion are controlled by the same organ.

The image of the glider propulsion that arises from the above considerations is represented diagramatically in Fig.5.

To start propulsion, the operator, who is suspended in sitting position with his feet resting on the trapeze 3,4, forces vibration of the system by bending his knees and hips. In the lower position he pushes up vigorously from the trapeze thus producing a downward propulsion stroke of the wing 1. During this stroke he adjusts the inclination β of the glider so as to maintain possibly constant incidence angle α, thus producing a thrust component. During the idle stroke the operator bends his knees and takes the primary position, beginning from which the cycle may be repeated.

Uninterrupted contact with the rigid control frame and the loose trapeze 3, 4 will enable accurate control and acceleration and retardation of the cycle, depending on the value of the propulsion force Z and other flight requirements. It enables also the operator to stop or resume propulsion.

VI. Energy Considerations of Oscillating-Wing Propulsion

In horizontal flight the entire power P is used for maintaining the motion at a velocity v. Under such conditions the familiar general relation

$$P\eta = \frac{L \cdot v}{75\,(L/D)} \qquad /12/$$

is valid. On the other hand, we have also, for wing-propulsion, the good approximate relation*.

$$P\eta_m\,\eta_k = \frac{L_p\,v_2}{75\,(L/D)_p} \qquad /13/$$

where

$$(L/D)_p = \int_0^{il_2} \frac{(L/D)\,dl_2}{il_2} \qquad /14/$$

Considering the energy relationships of wing propulsion we must first determine η_m, η and η_k.
In the case of wing propulsion of the type described, in which there are no transmission gears nor bearings, nor hydraulic control organs etc. the mechanical efficiency may be very high, the only losses being those of friction of the springs and in the suspension hinge. These losses can be reduced to negligible values so that it is legitimate to assume that $\eta_m = 1$.

If we are concerned with the overall efficiency of the wing it can be found, by dividing the Eqs./11/ by /12/ and bearing in mind that, $v/v_2 = 1/l_2$

$$\eta = \frac{L\;l\;(L/D)_p}{L_p\;l_2\;(L/D)} \cdot \eta_m\,\eta_k = \eta_a\,\eta_m\,\eta_k \qquad /15/$$

This simple relation shows the measures to be taken to obtain high η and emphasises the role that is played by the kinematic efficiency η_k.

In the case of a hang glider the principal means is very simple, which has already been emphasized, and lies literally in the hands of the operator. It consists in an appropriate control of the type F_ξ = const. without excessive overloading and with no undue unloading of the wing. This means wing operation at maximum $(L/D)_p$ with no variation of the incidence angle and transient drops in lift/drag of the wing reducing the value of the integral /14/. At the same time the trajectory of the wing should show possibly flat waves so that $1/l_2 \rightarrow 1$. Also L/L_p should also be near unity which will depend, as already known, from the type of control used and the weight of the system per unit power which depends, for horizontal flight, on its lift/drag ratio.

Another means for obtaining high propulsion efficiency depends on the design and consists in applying a possibly light glider structure, so that the ratio W_1/W /and therefore η_k/ is possibly high. The influence of that ratio is connected with the fact that the amplitude ratio h/h_1 decreases in direct proportion to the decrease in W_1/W /Fig.6/ which leads to an increased unnecessary motion of the weight W_1 and a reduced kinematic efficiency η_k. This decrease in η_k, which is still insignificant for $h_1/h = 0.5$ is difficult for theoretical analysis, because it is a consequence of the dissipation of the kinetic energy of excessive oscillation of the weight W_1.

From the above considerations it is inferred that the value $\eta = \eta_a\,\eta_m\,\eta_k$ may approach very closely unity. This conclusion is in agreement with the common belief that very high efficiency of wing propulsion can be achieved[9]. It is also conformed by the results of theoretical analysis[9,10], which shows that it is possible even for swinging wings, to attain a propulsion efficiency of $\eta = 0.8$.

It should be observed that high propulsion efficiency is in some sense a natural feature of wing propulsion, the propulsion organ, that is the wing, being weakly loaded and generating a low induced velocity.

A shortcoming of wing propulsion which is manifested during take-off of large birds is poor static efficiency and poor static thrust. This shortcoming is particularly important for oscillating wings with a narrow frequency range. Thus, take-off is a separate and difficult aerodynamic and technological problem of wing propulsion. It appears to be reasonable for the take-off run to use propulsion of another type.

To evaluate the power demand for horizontal flight of a hang glider we can use the relation /12/, from which we find, for instance, that if L/D = 10, which is possible, the propulsion power for a flight velocity v = 10 m/sec, a weight W = 93.5 kg and $\eta = 1$ should amount to P=1.25 HP, which exceeds considerably the permanent power available which is, for an operator in good athletic condition P = 0.4 HP approximately.

It follows that for wing propulsion of a hang glider by muscles we can expect, at most, climb of very short duration or reduced descent in long duration flight.

The reduction in descent can be expressed in the form of increased effective lift/drag ratio of the system. Defining the latter quantity as

$$(L/D)_{ef} = \frac{L}{D - F_t} \qquad /16/$$

where F_t is the mean thrust of the wing-propelled glider directed parallelly to the flight and different from the horizontal thrust F_ξ considered before, we find

$$(L/D)_{ef} = \frac{C_L}{C_D - \dfrac{150\,g\,P\,\eta}{v^3\,\gamma\,S}} = \frac{C_L}{C_D - C_T} \qquad /17/$$

* This relation follows from the assumption that the work of the pilot drag along his trajectory is equal to the work along the trajectory of the wing.

For a short-duration /about 5 minutes/ power of $P = 0.6$ HP, which is possible to afford and $v = 10$ m/s, $S = 20$ m^2, $\eta = 1$.

$$C_T = \frac{150 \cdot 9.81 \cdot 0.6}{10^3 \cdot 1.2 \cdot 20} = 0.037$$

Hence, for $(L/D)_p = 10$ at $C_Z = 0.75$, $C_D = 0.075$

$$(L/D)_{ef} = \frac{0.75}{0.075 - 0.037} = 19.8$$

This result shows the practical possibility to increase the lift/drag ratio to about twice its actual value and to reduce in the same proportion the descent of a hang glider, by applying wing propulsion. The reduction in descent is

$$\Delta w = \frac{75\ P \cdot \eta}{W} \qquad /18/$$

$$= \frac{75 \cdot 0.6 \cdot 1}{93.5} = 0.48 \text{ m/s}$$

It is observed that wing propulsion of a hang glider will be relatively less efficient for greater C_D, higher velocity v of the glider and, greater weight W. Thus, for instance, a reduction in descent of a conventional glider of 300 kg total weight would be by about 0.15 m/s only. This confirms the conclusion of Lippisch[2] that low weight and low flight velocity are more essential for muscle propulsion than high aerodynamic properties.

This feature is shown in a more clear manner by the relation /17/ written in the form

$$(D/L)_{ef} = D/L - \frac{75\ P\ \eta}{W\ v} \qquad /19/$$

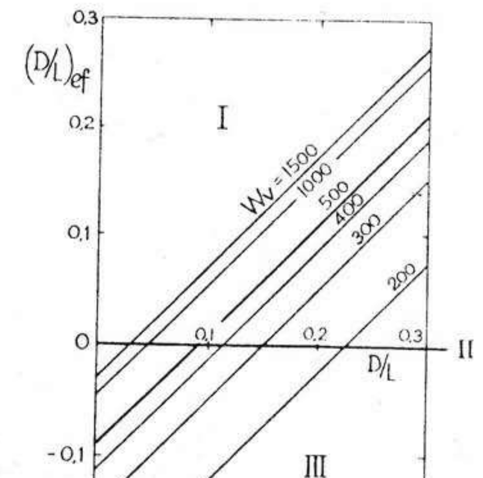

Fig.11 The influence of the total weight W and the flight velocity v, in the form of the Wv, on the relation between the inverse effective lift/drag and the inverse aerodynamic lift/drag of the pilot-glider system by means of a propulsion of P=0.6 HP and a propulsion efficiency $\eta = 1$

This relation has been used as a basis for the diagram of Fig.11 in which is represented, in a wider range, the influence of the product Wv on the efficiency of wing propulsion as determined $(L/D)_{ef}$, for a power $P = 0.6$ HP and $\eta = 1$. The square region I - corresponds to the conditions under which a power of 0.6 HP is insufficient for horizontal flight and only improves the effective lift/drag ratio. On the boundary II of that region it is possible to maintain horizontal flight and in the rectangular region III at negative values of $(L/D)_{ef}$, climb is possible.

VII. Some Aerodynamic Problems of Wing-propelled Hang Gliders

From the above considerations it follows that wing propulsion by pilot's muscles can improve considerably the performance of a hang glider, provided that its normal performance is sufficiently high. Thus, for instance, such a propulsion will give a poor effect for a hang glider with a double-cone Rogallo wing of a lift/drag ratio of 4 and a descent of about 2.5 m/sec, if the reduction in descent possible to achieve is about 0.5 m/sec, even for $\eta = 1$. In agreement with the diagram of Fig.11 this will enable an effective lift/drag ratio of somewhat less than 5.

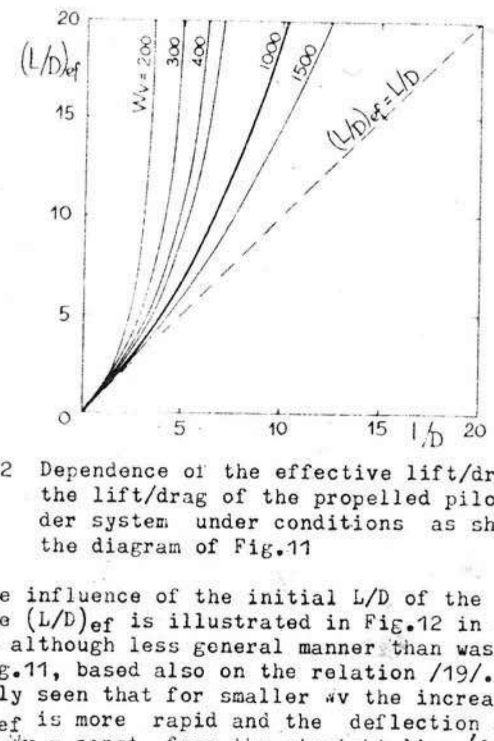

Fig.12 Dependence of the effective lift/drag on the lift/drag of the propelled pilot-glider system under conditions as shown in the diagram of Fig.11

The influence of the initial L/D of the system on the $(L/D)_{ef}$ is illustrated in Fig.12 in a more lucid although less general manner than was done in Fig.11, based also on the relation /19/. It is clearly seen that for smaller Wv the increase in $(L/D)_{ef}$ is more rapid and the deflection of the curve Wv = const. from the straight line $(L/D)_{ef} = L/D$ is greater. It follows that the reason for application and development of wing propulsion for a hang glider depends, in general on the possibility of design of an ultra-light wing with good aerodynamic properties. In this respect, with the existing materials and those that may be expected in the future, is very promising the stretched-membrane wing[11,12], the principle of which is shown in Fig.13. The essential feature of that wing, which has an arched profile, is that its lifting surface 2 is stiffened in the direction of flight by comb-like ribs 1, the profile re-

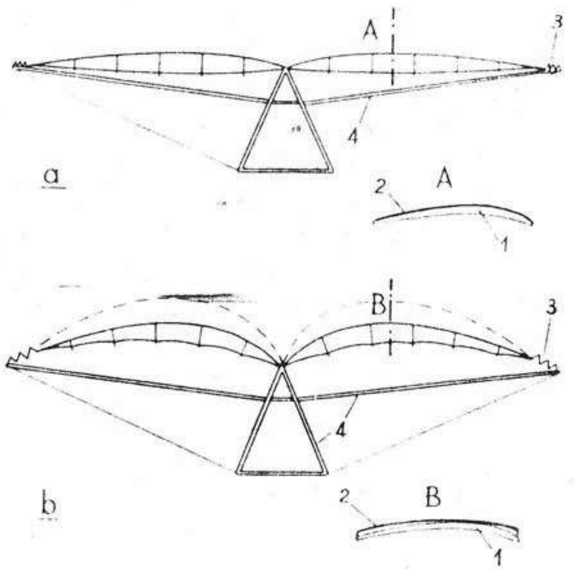

Fig.13 Diagram of the structure of a stretched--membrane wing:a- non-loaded wing,b- loaded wing elastically deformed

maining almost unchanged. The transversal elastic deformation is facilitated by the elastic fixing elements 3. An example of design of such a wing, built for sailing applications[13] in the form of a sailing hang glider, is shown in Fig.14.

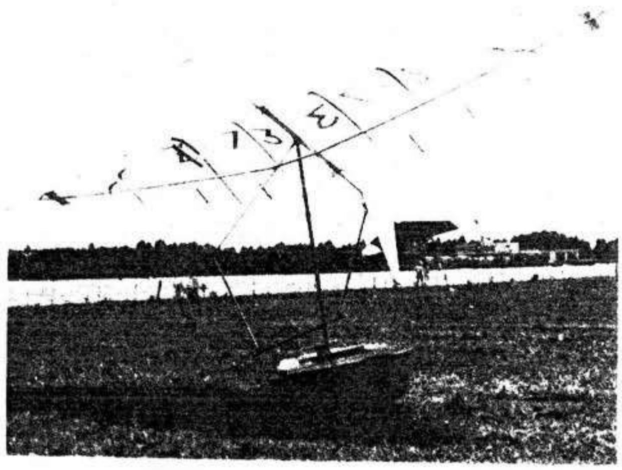

Fig.14 Stretched-membrane sailwing for sailing application. W_2 = 10 kg, S = 10 m^2

Fig.15 represents, for comparison, experimental polar curves a, b, c for light wings of various types and the expected polar curve d for a double-slot stretched-membrane wing. The curves show the aerodynamic quality of stretched-membrane wing with no slots over the entire range of incidence angles. It is better than the quality of Rogallo wings. If the aspect ratio increases, these differences increase also with further increase in lift/drag ratio, above 10.

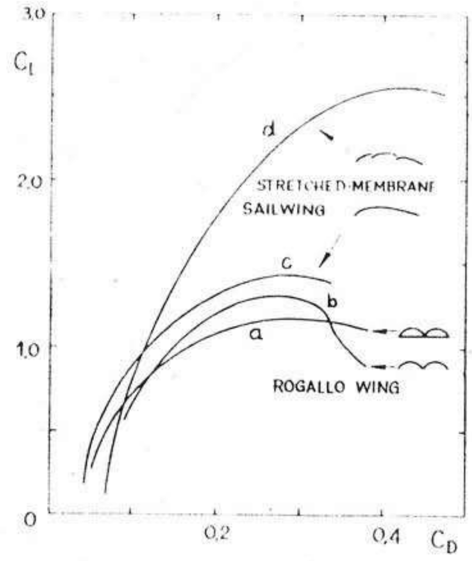

Fig.15 Confrontation of polar curves of stretched-membrane wings and Rogallo-type wings of aspect ratio A = 4

A serious aerodynamic problem of hang glider is the disadvantageous influence of the aerodynamic drag of the pilot on the lift/drag of the pilot--glider system. This lift/drag is determined by the relation

$$L/D = \frac{C_L}{C_{D_g} + C_{Dp}\ S_p/S} \qquad /20/$$

On the basis of the above relation for a pilot in a sitting position with C_{Dp} = 1, S_p = 0.6 m^2 and in a lying position with C_{Dp} = 0.5, S_p = 0.15 m^2 we have obtained for $(L/D)_g$ = 0.75/0.05 = 15 and $(L/D)_g$ = 0.75/0.025 = 30 four curves of L/D bounding the relevant regions in Fig.16. The dotted

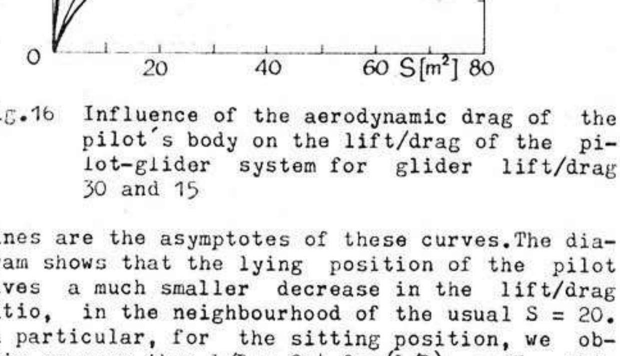

Fig.16 Influence of the aerodynamic drag of the pilot's body on the lift/drag of the pilot-glider system for glider lift/drag 30 and 15

lines are the asymptotes of these curves.The diagram shows that the lying position of the pilot gives a much smaller decrease in the lift/drag ratio, in the neighbourhood of the usual S = 20. In particular, for the sitting position, we obtain no more than L/D = 9.4 for $(L/D)_g$ = 15, while the lying position would enable us to attain $L/D = 13.8$. It follows that the drag of the operator's body will influence considerably the efficacy of wing propulsion of a hang glider, which depends in a decisive manner, as has been shown in Fig.11 and 12, on the lift/drag ratio of the system.

In addition, in the case of a wing, the load carrying skeleton of which is not accommodated in the interior of a thick airfoil, this being the case of the wing shown in Fig.13, there is also the influence of the skeleton on the lift/drag ratio of the system. It may be expected that with increased aspect ratio of the wing A and, therefore the wing span, the disadvantageous influence of the presence of the skeleton will grow so that if a certain A_{opt} has been reached, further increase of the aspect ratio will increase the general drag coefficient C_D of the system, therefore it will impair its lift/drag ratio. Indeed, if we write the expression for the drag coefficient of the system

$$C_D = C_{Di} = \frac{S_s}{S} C_{Ds} + \frac{S_e}{S} C_{De} + \frac{S_p}{S} C_{Dp} + C_{Df} \qquad /21/$$

where $C_{Di} = \varkappa C_L^2/\pi A$ coefficient of induced drag with $\varkappa = 1$ for elliptic distribution of circulation, then, taking into account the following linear relation between S_s and A

$$S_s = \frac{A}{A_i} S_{si} \qquad /22/$$

where S_{si} and A_i are the initial values, which are known and practically verified, we obtain, on differentiating /21/ and setting the result equal to zero:

$$\frac{\partial C_D}{\partial A} = \frac{C_L^2}{\pi A^2} + \frac{1}{A_i} \frac{S_{si}}{S} C_{Ds} = 0$$

$$A_{opt} = \left[\frac{A_i \, S C_L^2}{S_{si} \, C_{Ds}} \right]^{1/2}$$

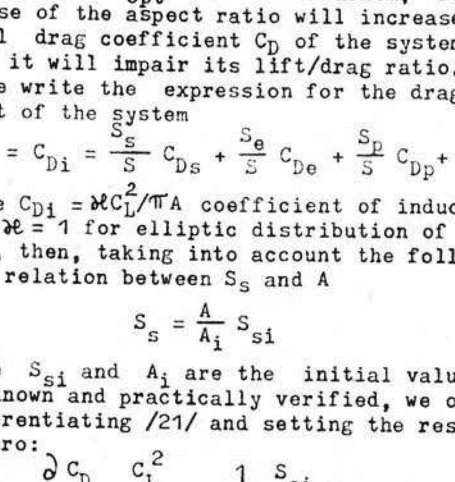

Fig.17 Influence of the drag coefficient C_{Ds} of the external skeleton of the wing on the optimum aspect ratio A_{opt} for which the lift/drag of the hang-glider is maximum

With values $A_i = 4$, $C_L = 0.75$, $S = 20 \text{ m}^2$, $S_{si} = 0.5 \text{ m}^2$ $/S/S_{si} = 40/$ which are feasible today, we obtain A_{opt} in function of C_{Ds} as represented in Fig.17, which shows that the application of a skeleton with streamlined cross-section and further reduction in S_{si} will enable considerable increase in the aspect ratio, in this way also the lift/drag ratio. Since the curves lie over the entire range of C_{Ds}, in a region of relatively large values of A_{opt} /9 to 20/, this means that there is considerable possibility for the development of hang gliders and their wing propulsion.

VIII. Final Remarks

The above considerations have shown that the hang glider with a wing performing translational oscillation is the simplest solution of the problem of wing propulsion. As compared with the propulsion by means of swinging wings /ornithopters/ imitating birds, it offers a number of considerable advantages, such as

- feasibility
- extraordinary simplicity of design
- more advantageous aerodynamic properties
- better propulsion efficiency
- better precision and facility of propulsion control
- lower weight
- lower costs
- better adaptability /if muscles are used/ to the anatomic features and psychophysical possibilities of man.

Its most essential advantage is that it is a feasible system, which has not yet proved to be the case of the swinging wing system, requiring elastic wing profiles and a difficult to realize complicated system of control of twist and pitch angle.

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