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THE TECHNOLOGICAL PROSPECTS FOR OSCILLATING-WING PROPULSION OF ULTRALIGHT GLIDERS

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THE TECHNOLOGICAL PROSPECTS FOR OSCILLATING-WING PROPULSION OF ULTRALIGHT GLIDERS

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Abstract

The subject of the consideration are basic mechanical and aerodynamical problems of oscillating-wing propulsion for a man-powered hang glider. This propulsion requires elastic suspension of the pilot. The drive is transmitted from the pilot's legs to a stiff-wing structure by a trapeze device. This simple type of propulsion may reach extreme efficiency if appropriate longitudinal control has been provided. Translational-motion oscillating wings are shown to be of many advantages as compared with swinging bird-like wings. The soundness of the explained idea of propulsion has been confirmed by morphology analysis and value engineering.

Nomenclature

A - aspect ratio

A_i - initial aspect ratio

C_D - drag coefficient of glider-pilot system

C_{De} - drag coefficient of the elastic suspension

C_{Df} - friction drag coefficient of the glider

C_{Dg} - drag coefficient of the glider

C_{Di} - induced drag coefficient of the glider

C_{Dp} - drag coefficient of pilot s body

C_{Ds} - drag coefficient of glider skeleton

C_L - lift coefficient

C_T - thrust coefficient of the wing

D - drag of the glider-pilot system

F_a - total aerodynamic force

F_t - thrust in flight direction

F_ζ - vertical aerodynamic force

F_ξ - horizontal aerodynamic force

g - acceleration due to gravity

H - elongation of the elastic suspension

H_s - static elongation of the elastic suspension

h - amplitude

i - number of parallel springs; integer

K - elastic suspension; its constant

k - constant of single spring

k_s - substitute spring constant

L - lift

L_p - mean lift in wing propelled flight

l - flight trajectory; its lenght per one cycle

$(L/D)_{ef}$ - effective lift/drag in powered flight

$(L/D)_p$ - average lift/drag of the oscillating pilot-glider system for propulsion

$(L/D)_g$ - lift/drag for the glider

n - load factor of the wing

P - power of propulsion

S - wing area

S_e - frontal area of the elastic suspension

S_p - frontal area of pilot's body

S_s - frontal area of the skeleton

S_{si} - initial frontal area of the skeleton

T - tension force of single spring

t - time

t_f - forced oscillation period

t_n - natural oscillation period

t_p - powered cycle period

t_r - real oscillation period

t_u - unpowered cycle period

W - weight

ΔW_2 - apparent weight increment of the wing

Δw - sink velocity decrease

v - flight velocity

Z - driving force produced by the pilot

α - incidence angle of the wing

β - pitch angle of the wing

γ - specific weight of the air

η - overall wing propulsion efficiency

η_k - kinematic efficiency of wing propulsion

η_m - mechanical efficiency of wing propulsion

ζ - vertical coordinate

ξ - horizontal coordinate

1 - subscript, concerning the pilot

2 - subscript, concerning the glider

I. Introduction

Wing propulsion of a flying device particularly with the use of human muscles has for very long been of interest to some minds. As an example shoving that the problem is still topical let us mention the recent paper of Upenieks[1] suggesting such a propulsion for a hang glider. However, more detailed analysis shows that Upenieks'

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ideas give rise to a number of doubts as to whether the general direction of the efforts hitherto made, with swinging bird-like wings, is correct and whether it is the only possible. The main purpose of the present paper is to give an answer to these questions and to consider a practical alternative.

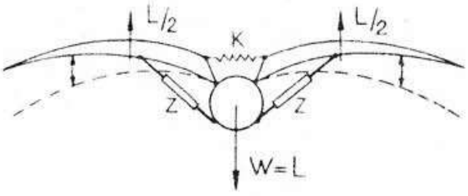

Fig.1 Principle of ornithopter propulsion

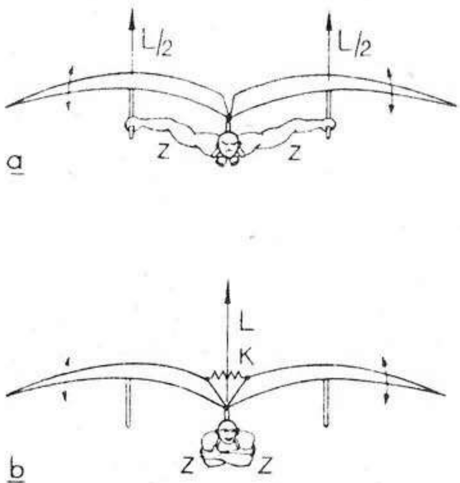

Fig.2 Illustration of the necessity of using an elastic element K relieving the muscles from performing excessive bio-mechanical work: a- non relieved bird-like system according to the conception of Leonardo da Vinci, b- a relieved system realized, for instance in a glider by A.M.Lippisch[2]

The reasonable efforts hitherto made to realize wing propulsion, according to Lippisch[2], for instance, take as a basis the system shown in Fig.1. In this system the wings are hinged to the body in which most of the mass W/g of the system is concentrated. Relatively light wings are moved in an oscillating manner by human muscles or, generally by jacks Z. In order to relieve the muscles, which are not adapted for a long static effort, from the task of counterbalancing the entire lift L/2 of the single wing and from the performing the excessive work, as is demonstrated in Fig.2, it is necessary that the wings should be mounted in an elastic manner by means of an elastic element K. Such a scheme requires in addition, for propelling purposes, that the aerodynamic force passing through the aerodynamic centre of the wing should twist the wing during the working stroke. The aim of this deformation, automatic or controlled, is to realize periodic variation of the pitch angle of the wing, thus producing a thrust component.

II. The Idea of Oscillating Wing Propulsion

The above arrangement imitates awkwardly the complicated but fully controlled motion of bird wings. However, methods of value analysis[3] and morphological analysis[4] show that close technical imitation is incorrect and not justified. It is incorrect, because the functions of birds' wings are, from the point of view of value analysis, multiple, the basic-functions being to make the animal survive and protect it, therefore they are completely different from those of mechanical wings, which are to produce effective lift and thrust. In addition close imitation is not justified, because the swinging motion of bird's wings is merely a consequence of the origin of the wings from the swinging limbs of Triassic quadruped reptiles, there being no reason for technical imitation of a consequence of this circumstance. Indeed, morphological considerations summarized in Fig.3 show that in addition to the circular motion of the lifting surfaces /helicopters/ and a cylindrical motion /Rohrbach's rotocopter/ or the swinging motion /ornithopter/ there is a possibility of reciprocating translational motion of the lifting surfaces, investigated first by Reifenstein[5] and analysend theoretically by Schmeidler[6].

This way of thinking leads us, as a result of forecasting based on the value analysis of the

Flight velocity m/sec	Type of motion of the lifting surfaces			
	Circular	Cylindrical	Swinging	Translational
0÷5			Insects and very small birds with wings vibrating at high frequency	There exist no NEW SOLUTION enabling static thrust
5 ÷ 20	Helicopters	Rotopters /eg. unrealized Rohrbach's concept/	Birds and ornithopters with non relieved wings. Ornithopters with relieved wings performing swinging oscillations	The NEW SOLUTION with relieved wings performing translatory oscillations /the most simple is a hang glider considered/
20÷100			Reinforced rigid ornithopter /very difficult to realize/	No NEW SOLUTION

Fig.3 Morphological box for propulsion systems by means of the lifting surfaces

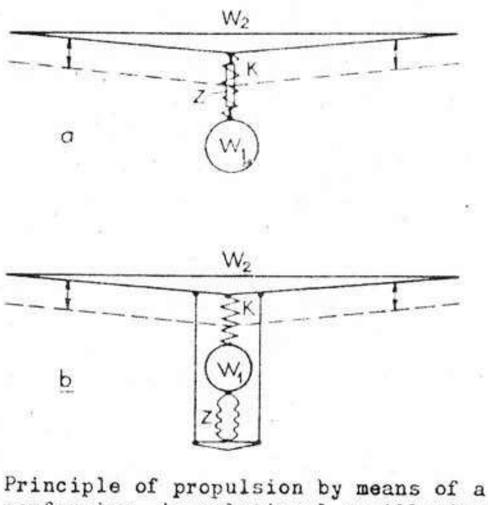

Fig.4 Principle of propulsion by means of a wing performing translational oscillations: a- with tensioned jack Z, b- with compressed jack Z

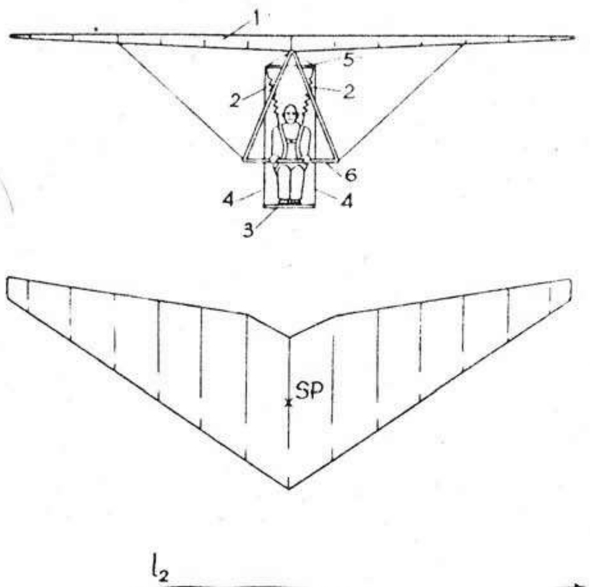

Fig.5 A relieved system with wings performing translational oscillation as applied to a hang glider: 1- wing, 2- springs, 3- transverse member of the trapeze, 4- cables of the trapeze, 5- spacer bar, 6- control bar, SP- suspension point of the pilot, l, l_1, l_2- trajectories of the system, the operator and the glider, respectively

arrangement shown in Fig.1 and the morphological approach, to the scheme as shown in Figs.4a and 4b. In this system the mass W_2/g of the wings and the remaining mass W_1/g joined by a spring K perform reciprocating strokes, thus oscillating in a direction normal to that of flight. The device of Fig.4b, with a trapeze and a compression jack Z /the jack in Fig.4a working in tension/ is well adapted for a hang glider, in which the task of the power jack may be done by pilot's legs. An example of design of a man-powered hang glider with oscillating wings is shown in Fig.5. This design differs generally from the scheme considered by Smith[7] by application of elastic suspension of the pilot. The main purpose of elastic suspension for the hang glider pilots is to eliminate considerable and uneffective bio-mecanical work of the excessively stressed muscles of the operator.

III. Oscillation of the Pilot-Glider System

The problem of oscillation of the pilot-glider system is fundamental for the analysis of the oscillating-wing propulsion of a glider. This system being composed of two masses: the pilot W_1/g and the glider W_2/g, we can assume in the first stage of analysis perfectly and elastically suspensed in air /Fig.6a/ with a constant vertical aerodynamic force F_ζ. For such a model the solution of the differential equations of vibrating motion leads us to the following formula for the period of natural harmonic and synchronous oscillation of the two masses

$$t_n = 2\pi \left[\frac{W_1}{igk} \; \frac{1}{1 + W_1/W_2} \right]^{1/2} \qquad /1/$$

where $ik = K = dT/dH = const.$ This oscillation and the corresponding amplitudes h_1 and h_2 are shown in function of time in Fig.6a. A more complicated model, approaching better the reality is shown in Fig.6b. It differs from the former by the presence of an excitation force Z and a variable vertical aerodynamic force F_ζ. These forces are functions of the relative displacement H of the two masses W_1/g and W_2/g or the time t and their variation which is synchronous with the oscillation of the system will also influence the oscillation period.

For accurate mathematical description of the real oscillation it would therefore be necessary to know or to prescribe the form of these functions, which is premature in the present state of knowledge of oscillating wing propulsion and exceeds the scope of the present paper. We shall confine us, therefore, to an analysis of the influence of the forces Z and F_ζ on the oscillation period t_n on the basis of the relation /1/.

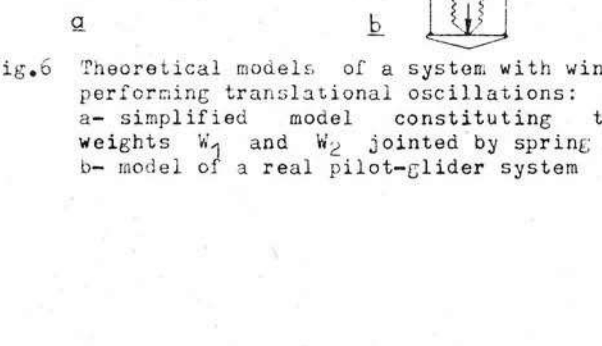

Fig.6 Theoretical models of a system with wings performing translational oscillations: a- simplified model constituting two weights W_1 and W_2 jointed by spring K, b- model of a real pilot-glider system

The force Z is a variable force exerted periodically by operator's muscles during successive half-periods of oscillation of the system. This force may be applied by the operator in various manners, a more detailed analysis of which is a matter of anatomy and physiology. In our simple considerations it will be most convenient to assume that it is proportional to the elongation of the spring. Such an assumption enables us to express it in terms of a substitute constant $k_S = dZ/dH = const.$ which may be added to the constant k in the Eq./1/. It follows immediately that an increase in Z and, as a consequence, k_S, reduces the propulsion half-period. Thus, the Eq./1/ may be written in a more general form, determining the frequency of forced oscillation t_f, in the case of $F_\xi = const.$

$$t_f = 2\pi \left[\frac{W_1}{ig\,(k+k_s)} \; \frac{1}{1 + W_1/W_2} \right]^{1/2} \qquad /2/$$

If we are concerned with the influence of the variation of the external force F_ξ acting on the system, the problem is more difficult for quantitative analysis. Let us observe, however, that an increase in the force F_ξ, caused by a variation in an appropriate manner of the angle of incidence during the period of relative approach of the weights W_1 and W_2, will produce the same effect as would be obtained by an increase in inertia of the weight W_2 that is an increase in its weight by an apparent value ΔW_2.

From the Eqs./2/ and /1/ it follows, therefore, that an increase in the force F_ξ, that is an increase in W_2 by ΔW_2 will prolong the period t_f. Conversely, a decrease in F_ξ below its conventional value, $W = W_1 + W_2$, for instance, will give a negative ΔW_2 and a reduced period t_f.

There are two inferences from the above remarks.

1. The oscillation of the pilot-glider system will be asymmetric in general, that is the propulsion half-period will differ from the idling half-period.
2. The oscillation will be aperiodic if the operator does not exert an exactly periodic force and if he does not perform an exactly periodic control of the incidence angle.

The method for determining k_s and the optimum elastic properties of the suspension system of the operator and the method for determining the variability range of the oscillation frequency and its asymmetry can be best illustrated by numerical data. The values assumed for computation have the character of an example and may not be optimum because they have not been the object of more detailed analysis.

The numerical value of the period must be assumed as fundamental. This follows from the fact that, for physiological reasons, there is a definite frequency of bending of knees and hips, for which maximum power is obtained with minimum fatigue. The elastic properties of the system must be adjusted to this frequency. It may be assumed that this optimum frequency corresponds, similarly to the case of a cyclist, to $t_n = 1$ sec. Next, we must fix the expected weights of the system $W_1 = 80$ kg and $W_2 = 13.5$ kg, for instance, and use these data to compute from the relation /1/, the constant k of a single spring of the suspension system which have $i = 2$, for instance, as in Fig.5. Assuming, for simplicity, parallel springs we obtain

$$k = \frac{1}{2}\left(\frac{2\pi}{t_n}\right)^2 \frac{W_1/g}{1+W_1/W_2} = \frac{1}{2}\left(\frac{2\pi}{1}\right)^2 \frac{80/9.81}{1+80/13.5} = 23 \text{ kg/m}$$

This means that the lower ends of the springs /which are linear/ will oscillate about the static equilibrium position H_s at a frequency of $1/t_n$ and an amplitude $h = h_1 + h_2$, which should be confined, for ergonomy reasons, to a range of about 0.3 m.

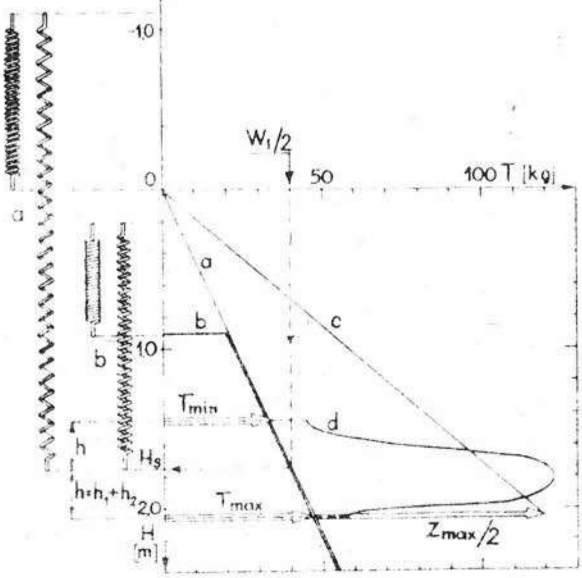

Fig.7 Confrontation of the properties of the suspension spring non-pretentioned a and pretensioned b and represensation of the substitute characteristic c of the real characteristic d for the force Z exerted by the feet on the trapeze.

It should also be observed that, for the obtainment of the above values of t_n and k for a length of the elongated spring not greater than about 1.5 m, the coils of the spring must be pressed together in the undeformed state with considerable initial tension. Such a spring is represented in Fig.7b showing also its characteristic b, from which it follows that the initial pressure between coils, produced by initial torsion of the wire during the winding process of the spring should be, in the case considered, about 20 kg. Application of a spring made of non twisted wire would lead to too long a spring an example of which is represented in Fig.7a. The vertical scale of lengths shown in that figure enables us to see that the length of such a spring would amount, in the loaded state, to 2.8 m. This length is unacceptable, in view of the possibility of accomodation within the glider structure, which is of limited dimensions.

Turning now to the problem of frequency variation range, we must next determine k_s. To this end we must determine the mean value of the force Z for the expected values of t_p and h and the maximum short-duration power produced by human muscles, which is about $P_{max} = 1$ HP.

Since

$$P = \frac{2hZ}{75\ t_p} \qquad /3/$$

therefore

$$Z = \frac{75\ P_{max}\ t_p}{2\ h} = \frac{75 \cdot 1 \cdot 1}{2 \cdot 0.3} = 125\ \text{kg}$$

which seems to be realizable by an operator of average athletic condition for a period of a few seconds and for a few working impulses of the muscles of the operator's legs.

By considering the diagram of Fig.7 showing the action of the force Z_{max}/i and by drawing its linear characteristic c, constituting an approximation to the real characteristic d, we can write the relation

$$\frac{Z_{max}/i}{k_s} = \frac{T_{max}}{k} \qquad /4/$$

and hence, for the values Z_{max} and T_{max} as read from the diagram of Fig.7, the substitute spring constant

$$k_s = k\,\frac{Z_{max}/i}{T_{max}} = 23\ \frac{72.5}{47.5} = 35\ \text{kg/m}$$

To determine the variability range of the oscillation period it is also necessary to know the values of the vertical aerodynamic force acting on the wing. The vertical force F_ζ is a variable aerodynamic force, the lowest value of which, in propelled flight now considered, is equal to

$$F_{\zeta\,min} = i\ T_{min} + W_2 = 2 \cdot 32.5 + 13.5 = 78.5 \qquad /5/$$

where T_{min} is the force of a single spring under minimum tension.

The highest possible value of F_ζ depends in turn on the excess of C_L which may be made use of by the operator under particular conditions of control of the incidence angle. Assuming that $C_{Lmax}/C_L = 2.5$, we find

$$F_{\zeta\,max} = (W_1 + W_2)\ C_{Lmax}/C_L = (80 + 13.5)\ 2.5 = 234\ \text{kg} \qquad /6/$$

when the normal force in glide being

$$F_\zeta = W_1 + W_2 = 80 + 13.5 = 93.5\ \text{kg} \qquad /7/$$

Knowing the above values we can proceed to evaluate the oscillation periods and their variability range. The natural frequency for F_ζ = const. and $Z = 0$ is, according to the assumption and Eq./1/, $t_n = 1$ sec as in the case a, Fig.6.

This period is at the same time the period of the propulsion stroke for the particular conditions of $F_\zeta - /iT + W_2/ = Z$, that is if the propelling force Z is immediately equilibrated by an increase in the force F_ζ above the value $iT + W_2$ for natural oscillation. This is possible in practice with a very accurate and careful control of the inclination angle of the glider. A drawback of such a control is the occurence of overloads on the structure, which means non-optimum operating conditions of the wing under variable lift.

In agreement with the relation /2/ a much shorter vibration period is obtained if the propelling stroke is performed according to the rule F_ζ = const. for $Z > 0$. Then we have

$$t_f = 2\pi \left[\frac{80}{2 \cdot 9.81\ /23+35/}\ \frac{1}{1+80/13.5}\right]^{1/2} = 0.63\ \text{sec}$$

which requires also a very accurate control by varying the inclination angle of the glider, but in a broader range of angles than before. An advantage of such a control is that there are no overloads on the wing, which can operate under constant conditions at maximum lift/drag ratio and a constant load.

The calculated values of t_n, t_f and F_ζ enable appropriate determination of the propulsion period t_p for various propulsion ways, with different values of F_ζ, by linear interpolation or extrapolation according to the relation.

$$t_p = t_f + \frac{F_\zeta - W}{Z}\ /t_n - t_f/ \qquad /8/$$

This relation enables us to avoid complicated analysis, which may require the determination of ΔW_2, and to determine the oscillation period for intermediate ways of control and also to obtain t_{pmax} for $F_\zeta - W > Z$ and t_{pmin} for $F_\zeta - W < 0$ which determines the maximum possible variability range of t_n. In the numerical example considered we have $t_{pmax} = 1.05$ sec, $t_{pmin} = 0.56$ sec.

If we are concerned with t_u, for the idling stroke, it is known that in the particular case of F_ζ = const. it is determined by the relation /1/. It may be influenced, however, in a wide range by the operator who decides on the way of oscillation damping during the idling stroke. He decides also on the form in which the kinetic energy imparted to the two masses during the propulsion stroke is used. This energy may be used, for instance for climbing, with $F_\zeta > W$, the operator resting for a while on the trapeze thus braking the return motion of the masses, which prolongs t_u.

In view of the asymmetry of oscillation a single cycle of which is composed of a short propulsion stroke $t_p/2$ and a longer idling stroke $t_u/2$, the real period is

$$t_r = 0.5\ /t_p + t_u/ \qquad /9/$$

Assuming for the numerical example considered that $t_u = t_n$, we find, for instance, that $0.78 < t_r < 1$. It may be expected, however, that the practical variability range of t_r will be wider. A more accurate determination of that range would require more detailed considerations, however.

IV. Kinematics of Oscillating-Wing Propulsion

In stationary glide, with no propulsion and no oscillation, the motion of the glider, the operator and the centre of gravity of the system as a whole will proceed along trajectories as shown in Fig.8a. They are parallel straight lines sloping at D/L.

If the operator makes the system oscillate, then, if no energy is supplied and if constant angle of incidence and constant vertical aerodynamic force F_ζ are preserved, the motion of the glider and the pilot will proceed along sinusoidal trajectories as represented in Fig.8b. The