NATIONAL FREE FLIGHT SOCIETY

REPORT OF THE TWENTY-FOURTH ANNUAL SYMPOSIUM OF THE NFFS

1991

A STUDY OF THE START AND SPEEDING UP OF AN F-1-A GLIDER ON A TOWLINE WITH THE USE OF A MATHEMATICAL MODEL

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FOREWORD

This article presents some of the research results in flying models flight theory developed by the authors at the Moscow Aviation Institute during recent years.

A mathematical model of the process of acceleration of a glider on a towline by a sportsman and a mathematical model of the process of launch, climb, and leveling of the glider in free flight with a controlled stabilizer are described. The simulation results of line acceleration and launch for a standard F-1-A model are presented. Also, research results are described for the influence of some parameters of the glider, line, sportsman and atmosphere on the acceleration of the glider to reach the maximum velocity (energy) at launch.

For the start with pitch control (start with "bunt"), the selection of control was performed at which desired trajectories of a climb and steady glide transition are ensured. The research results demonstrate some factors that influence the climb of the glider.

The mathematical models are implemented in complex computer programs allowing the study of different items in the design of free-flight models and remotely piloted vehicles.

The authors express thanks to Professor V.S. Brusov and Doctor R. Ch. Targamadze for their help with this work and the valuable comments that they provided.

In this article the USSR accepted aerodynamics and flight dynamics symbols are used (with the exception that σ is used in place of the symbol æ, *Eds.*).

The authors would be grateful for comments and responses on this work.

INTRODUCTION

If one thinks about the question of what the success of a sportsman in the F-1-A glider class depends on, these would be the qualities of a sportsman himself, weather conditions, model aircraft flight properties and high start. The best mutual combination of these factors plus some good fortune will produce consistently high results.

The development of model aircraft technology on the contemporary stage leads to improvement of model mechanization and the use of "peak" flight modes that provide an advantage in competitions. In this situation the use of mathematical models permits considerable reduction in search for and development of new solutions. From the other side, a possibility arises to exclude dead-end development directions not leading to design success even before the construction of a very dear and labor consuming sports model airplane.

This article deals with research on a mathematical model of a glider speeding up on a towline by a sportsman, and of the initial flight phase after the line is released.

A high glider start allows advantages not only in the number of meters gained, as many sportsman think. The authors have had an opportunity, on the basis of their own experience, to make sure that an increment of height of 10-15 m at the start will lead to qualitative changes in the tactics of a sportsman, broadening the range of his possibilities to get to a thermal. With each climbed meter the model aircraft will reach more and more favorable conditions, in view of ascendent flow forces, and due to these the results increase not in simple proportion to height, but, rather, in geometric progression.

The authors have always been interested in what influences a glider start; why it seems identical model aircraft start differently; and what are the influences of line properties, abilities of a sportsman, weather conditions, and various model parameters on the height of the start. These questions have become paramount with the stormy development of starts with pitch control.

At close examination the interaction between model aircraft, running sportsman, and line happened to be so complicated that intuitive thinking was in vain to explain in depth the model motion dynamics during speeding up on a line and at the start. Mathematical models of these processes were created and studied. The results of simulation closely coincided with practice and gave not only the true qualitative picture of the process, but permitted some important quantitative evaluations of various parameters as well. The authors used these results for construction of several model aircraft in 1990. It is necessary to emphasize that a mathematical model allows the determination of optimum ratios between many parameters of the glider, sportsman and line, to provide a maximum high start and to realize physical properties of a sportsman in the best way.

MATHEMATICAL MODEL

Overview and Main Assumptions

There was a task in front of the authors to describe in mathematical form the motion of a glider model while it is accelerated on a towing-line by a sportsman, for the aim of estimation of the influence of the various glider, line, sportsman, and atmosphere parameters on the possibility of reaching the maximum glider velocity (energy).

Another task was to describe free flight with a controlled stabilizer for the mathematical simulation of a glider starting with a "bunt".

In the mathematical model proposed by the authors, to solve the tasks specified, non-free motion of a glider in a vertical plane is viewed. A glider is represented as a rigid body, and aerodynamic loads are determined with phase (state) variables at any moment of motion. A towline is a rectilinear extensible thread with mass and air drag. One end of the line is fixed to a model airplane, the other one moves along the surface of the earth with a given velocity.

The behavior of a sportsman is described using the available speed, V_A, with which he runs at the time of model starting, and the ultimate force T_{max} in a line which he controls in order not to break the model. It is assumed that the force, T, in the line is less than T_{max} and does not influence the dynamics of sportsman movement.

A diagram of the forces acting in the system comprising the sportsman, line, and glider is shown in Fig. 1.

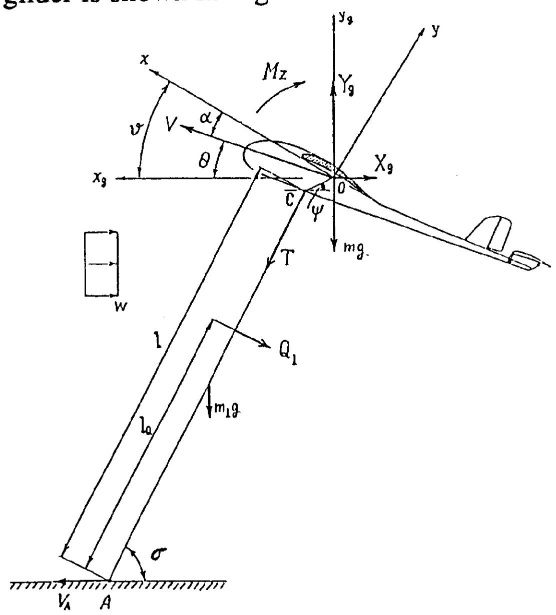

Figure 1. Diagram of forces for sportsman, line, and glider.

The diagram has the following designations:

- O – glider center of gravity (C.G.);
- C – point of line fixation to glider;
- A – point which moves along the earth surface with a set velocity V_A (sportsman towing a model);
- l – line length;
- l_H – distance from glider C.G. to point C;
- T – line tension force;
- X_g, Y_g – projections of glider aerodynamic force on normal axes x_g, y_g, respectively;
- M_z – aerodynamic pitching moment;

$$Y_g = (C_y \cos\vartheta - C_x \sin\vartheta)\frac{\rho V^2}{2} S;$$

$$X_g = (C_x \cos\vartheta - C_y \sin\vartheta)\frac{\rho V^2}{2} S;$$

$$M_z = m_z \frac{\rho V^2}{2} S \; b_a$$

where:

- ϑ – pitch angle;
- ρ – air density;
- V – speed of C.G.;
- S – wing area;
- b_a – mean aerodynamic chord (MAC) of wing;
- C_y, C_x – lift and drag aerodynamic coefficients, respectively, in a body axis system (direction of body axis Ox coincides with wing chord);
- g – acceleration of gravity,
- m, m_l – glider and line masses, respectively;
- σ – angle between towline and local horizontal plane;
- ψ – angle between OC direction and local horizontal plane;
- Q_l – the resultant of line air drag force;
- l_Q – arm of application of the resultant of line air drag force.

The present detailed elaboration of the mathematical model permits evaluation of the influence of basic factors pertaining to the speeding up of a glider. Let us now consider in detail the components of the mathematical model.

Aerodynamics

Aerodynamic characteristics depending on glider phase variables can be identified approximately according to the known polars of infinite-span wing and stabilizer airfoil sections. These are available from wind tunnel tests and can be represented as nonlinear functions of the angle of attack α and Reynolds number Re. We consider a lay-out diagram: "without horizontal tail" (WHT) + "horizontal tail" (HT). This allows us to study the influence of stabilizer angle on the characteristics of speeding up, and to carry out pitch control after the release of the line.

A force balance diagram is given in Fig. 2. We ignore the participation of the fuselage in the creation of lift, i.e.,

$$C_{ya\,WHT} = C_{ya\,w} \quad (C_{ya\,F} = 0)$$

$$C_{ya\,w} = f(Re_w, \alpha, \lambda_e)$$

$$C_{ya\,HT} = f(Re_{HT}, \alpha_{HT}, \lambda_{e\,HT}).$$

The drag of the WHT gilder consists of the profile and induced wing drag and that of the fuselage:

$$C_{xa\,WHT} = C_{x\,p\,w}(Re_w, \alpha, \lambda{=}\infty) + \frac{C^2_{ya\,WHT}}{\pi \lambda_e} + C_{x\,F}$$

where λ_e is the effective wing aspect ratio. For rectangular wings λ_e may be approximated as

$$\lambda_e = \frac{\lambda}{1 + 0.008\,\lambda}.$$

Here λ is the geometrical wing aspect ratio, $\lambda = l_w^2 / S$, where l_w is the wing span and S is the wing area.

The fuselage drag $C_{x\,F}$ is estimated as friction drag of all the fuselage elements. Fuselage interference with the wing and HT can be ignored because of the small ratio between fuselage diameter and wing span. Similarly HT drag is to be determined:

$$C_{xa\,HT} = C_{x\,p\,HT}(Re_{HT}, \alpha_{HT}, \lambda_{HT} = \infty) + \frac{C^2_{ya\,HT}}{\pi \lambda_{e\,HT}} .$$

The HT angle of attack in steady flight α_{HT} is

$$\alpha_{HT} = \alpha - \varepsilon + \varphi_{HT} ,$$

where ε is the downwash angle in the field of the HT given by

$$\varepsilon = \frac{2}{\pi \lambda_e} C_{ya\,w} ,$$

and φ_{HT} is the horizontal tail setting angle (from body axis Ox) used to adjust gliding flight and pitch control at the start after line release.

The total lift and drag coefficients for the entire glider are:

$$C_{ya} = C_{ya\,WHT} + \bar{S}_{HT}\, k_{HT}\, (C_{ya\,HT} \cos \varepsilon - C_{xa\,HT} \sin \varepsilon)$$

and

$$C_{xa} = C_{xa\,WHT} + \bar{S}_{HT}\, k_{HT}\, (C_{ya\,HT} \sin \varepsilon + C_{xa\,HT} \cos \varepsilon),$$

respectively, where $\bar{S}_{HT}$ is a relative HT area:

$$\bar{S}_{HT} = \frac{S_{HT}}{S}$$

and k_{HT} is the coefficient of current braking in the field of the HT.

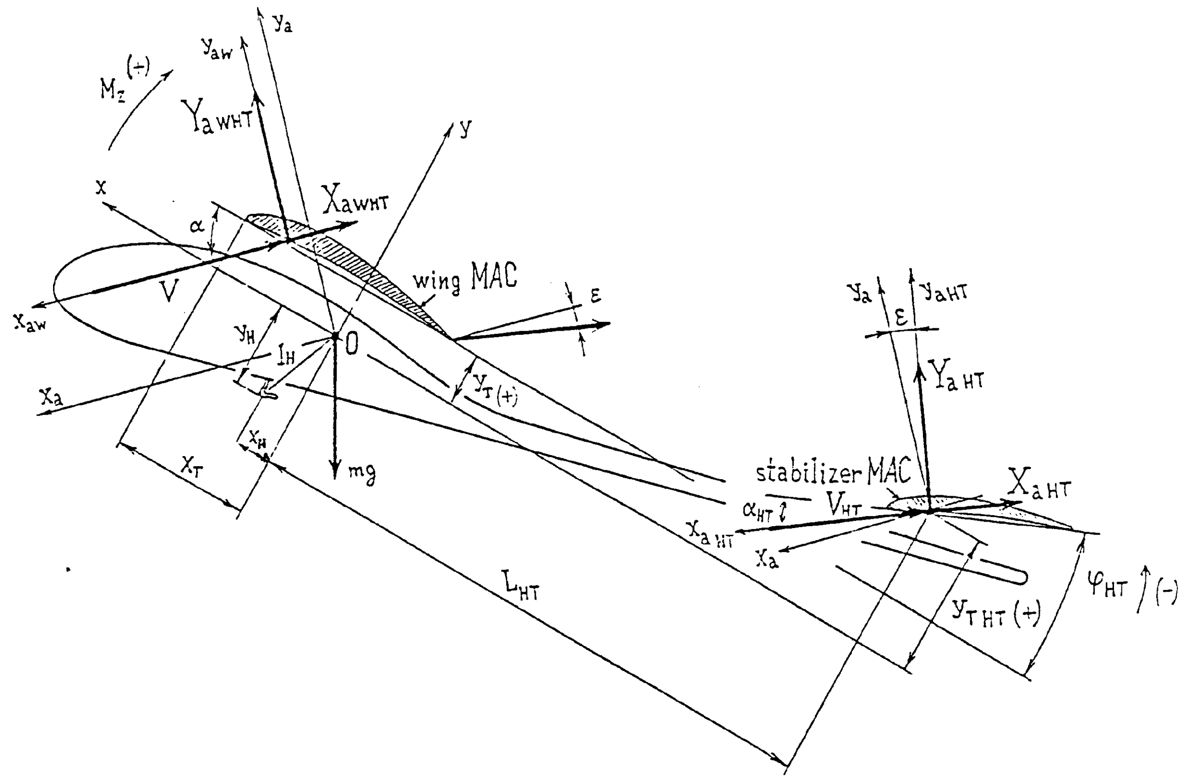

Figure 2. Diagram of Aerodynamic Forces

We ignore the fuselage contribution to the WHT glider longitudinal moment:

$$m_{z\,WHT} = m_{z\,0.25\,w} + (\bar{x} - 0.25)\,C_{y\,WHT} + \bar{y}\,C_{x\,WHT},$$

where $C_{y\,WHT}$, $C_{x\,WHT}$ are WHT glider lift and drag coefficients, respectively, in a body axis:

$$C_{y\,WHT} = C_{ya\,WHT}\cos\alpha + C_{xa\,WHT}\sin\alpha$$

$$C_{x\,WHT} = C_{xa\,WHT}\cos\alpha - C_{ya\,WHT}\sin\alpha,$$

$m_{z\;0.25\;w} = f\,(Re_w, \alpha)$ is the wing pitch moment coefficient about 0.25 wing MAC, and $\bar{x}_T$, $\bar{y}_T$ are the horizontal and vertical relative coordinates of the C.G., respectively, referred to wing MAC.

A complete pitch moment is

$$m_z = m_{z\,WHT} - \bar{S}_{HT} k_{HT} \left(\bar{L}_{HT}\, C_{y\,HT} - m_{z\,0.25\,HT} \frac{b_{a\,HT}}{b_a} + \bar{y}_{T\,HT}\, C_{x\,HT} \right)$$

where

$$C_{y\,HT} = C_{ya\,HT}\cos(\alpha - \varepsilon) + C_{xa\,HT}\sin(\alpha - \varepsilon)$$

$$C_{x\,HT} = C_{xa\,HT}\cos(\alpha - \varepsilon) - C_{ya\,HT}\sin(\alpha - \varepsilon),$$

$\bar{L}_{HT}$ is the relative HT arm given by

$$\bar{L}_{HT} = \frac{L_{HT}}{b_a},$$

$b_{a\,HT}$ is the mean aerodynamic chord (MAC) of the horizontal tail, $m_{z\;0.25\;HT} = f\,(Re_{HT}, \alpha_{HT})$ is the stabilizer pitch moment coefficient about 0.25 MAC of HT, and $\bar{y}_{T\;HT}$ is the relative vertical coordinate of the stabilizer position in relation to the glider C.G. referred to wing MAC.

A pitch moment component produced by a glider rotating movement is identified through the increment of the stabilizer angle of attack linked to pitch rate ω_z:

$$\Delta\alpha(\omega_z) = \arctan\left(\frac{\omega_z\, b_a\, \bar{L}_{HT}}{V\sqrt{k_{HT}}} \right).$$

Then, the local angle of attack of the HT is:

$$\alpha_{HT} = \alpha - \varepsilon + \varphi_{HT} + \Delta\alpha(\omega_z)$$

We ignore the contribution of the fuselage and wing to the creation of a longitudinal damping moment, as according to our estimates, their share in this moment for conventional glider lay-outs does not exceed 1 percent.

Generally, modelers strive to achieve an "ideal" trajectory of the glider during climb and transition, i.e., immediately after the climb the phase variables should have their steady-state values. In such trajectories the part of the pitch damping moment due to the rate of change of the angle of attack is 2–3 percent of the complete pitch damping moment, as can be explained with peculiarities of the lay-out diagram of an F-1-A model, as well as with the small values of the rate $\dot{\alpha}$ on the "ideal" trajectories. Therefore, for the flight modes considered here, we can ignore non-stationary effects of flow about the glider.

A summary calculation of glider aerodynamics includes the determination of C_{xa}, C_{ya}, and m_z coefficients, depending on the flight velocity V, the angle of attack α, and the pitch angular velocity ω_z at the set value of the stabilizer position φ_{HT}.

Free Flight and Balance

The differential equations of longitudinal motion for gliding flight of a rigid plane are:

$$\dot{V} = -\frac{1}{m}(X_a + mg\sin\theta)$$

$$
\begin{aligned}
\dot{\theta} &= \frac{1}{m V} (Y_a - mg \cos \theta) \\
\dot{\vartheta} &= \omega_z \qquad (1) \\
\dot{\omega}_z &= \frac{M_z}{J_z} \\
\dot{H} &= V \sin \theta \\
\dot{D} &= V \cos \theta ,
\end{aligned}
$$

where J_z is the glider moment of inertia in relation to Oz body axis, D is the horizontal distance travelled by the glider, H is the flight height, θ is the flight path angle,

$$Y_a = C_{ya} (V, \alpha, \omega_z, \varphi_{HT}) \frac{\rho V^2}{2} S,$$

$$X_a = C_{xa} (V, \alpha, \omega_z, \varphi_{HT}) \frac{\rho V^2}{2} S,$$

and

$$M_z = m_z (V, \alpha, \omega_z, \varphi_{HT}) \frac{\rho V^2}{2} S b_a.$$

The control φ_{HT} unambiguously defines a mode of the established glide (V, α, θ). A change of any glider parameter or control φ_{HT} leads to a change in the gliding mode.

Usually modelers seek to adjust a model airplane in such a way that the rate of descent for the established glide will be minimum. For this aim φ^*_{HT} of a glider is determined by way of repeated starts. A similar process is formalized in a procedure of selection of the balance of value φ^*_{HT} that provides the least descending velocity V_y in steady-state flight:

$$\begin{cases} \varphi^*_{HT} = \arg\min V_y (V, \alpha, \varphi_{HT}) \\ M_z (V, \alpha, \varphi^*_{HT}) = 0 \end{cases} .$$

It can be shown that at low gliding angles θ, the minimum realizable rate of descent is:

$$V_y = \sqrt{\frac{2 m g}{\rho S}} \frac{C_{xa} (V, \alpha, \varphi_{HT})}{C^{1.5}_{ya} (V, \alpha, \varphi_{HT})} .$$

Towline

A rectilinear and tensile line can be described with a second-order differential equation:

$$m \ddot{\delta} + k_1 \dot{\delta} + k_0 \delta = F (t),$$

where δ is an elongation increment of the line from its load; k_0 is a line rigidity coefficient; k_1 is a damping coefficient; $\dot{\delta}$, $\ddot{\delta}$ are the first and second derivatives, respectively, of δ in time; m is the glider mass; and F (t) is an external disturbing force. A diagram of the line tension process is given in Fig. 3. Here

$$l = L + \delta ,$$

where L is the line length without load and l is the line length with load.

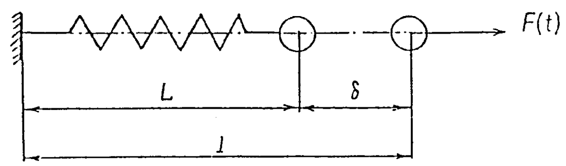

Figure 3. Schematic Diagram of Towline Tension

For the determination of line air drag it was supposed that the line is a cylindrical rod with a given diameter having a constant drag coefficient (not depending on the line Re number). A drag force of the element ds is proportional to the square of the velocity projection on a direction perpendicular to the line (see Fig. 4):

$$
\begin{aligned}
dQ_l (s) &= C_{xl} \frac{\rho V_l^2 (s)}{2} D_l ds \\
&= q (s) ds ,
\end{aligned}
$$

where C_{xl} is the drag coefficient for flow about the cylinder referred to its frontal area, D_l is the line diameter, q(s) is the air drag force distributed along the line, and $V_\perp$ is the velocity projection on the direction perpendicular to the line:

$$V_\perp = V \sin(\theta + \sigma)$$
$$= V_y \cos\sigma + (V_x + w)\sin\sigma .$$

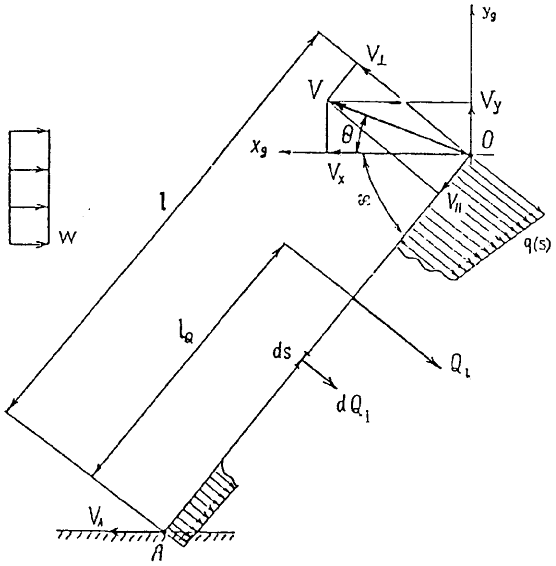

Figure 4. Drag Forces on the Towline

The drag force of the entire line is derived by integration along the line:

$$Q_l = \int_0^l q(s)\,ds$$

$$= \frac{\rho D_l C_{xl}}{2} \int_0^l \left(V_y \cos\sigma + (V_x + w)\sin\sigma\right)^2 ds$$

where:

$$V_x(s) = V_A + s \sin\sigma\,\dot\sigma ;$$

$$V_y(s) = s \cos\sigma\,\dot\sigma ;$$

and w is the wind velocity (supposed to be constant as a function of height).

Summarizing we get:

$$Q_l = 0.5\, C_{xl}\, \rho\, D_l\, l \left(\frac{l^2 \dot\sigma^2}{3} + l\,(V_A + w)\,\dot\sigma \sin\sigma + (V_A + w)^2 \sin^2\sigma\right) .$$

A point to apply the resultant of line's drag force is determined from the condition:

$$l_Q = \frac{\int_0^l q(s)\, s\, ds}{\int_0^l q(s)\, ds}$$

$$= l\left\{\tfrac{1}{4}\, l^2\, \dot\sigma^2 + \tfrac{2}{3}\,(V_A + w)\,\dot\sigma\, l \sin\sigma + \tfrac{1}{2}\,(V_A + w)^2 \sin^2\sigma\right\}$$
$$\div \left\{\tfrac{1}{3}\, l^2\, \dot\sigma^2 + (V_A + w)\,\dot\sigma\, l \sin\sigma + (V_A + w)^2 \sin^2\sigma\right\}$$

Sportsman

The dynamics of a model at the time of speeding up are defined by the interaction of a number of factors. These are the motion of the sportsman, various model properties, characteristics of the line, and weather conditions. Thus, if one does not grasp how a sportsman moves and does not formalize it into mathematical dependencies, it is impossible to create a general model of the speeding up of a glider on a line.

A start with pitch control much simplifies the characteristics of a sportsman's movement. He is required to begin running in time (to prevent decline of line tension and to prevent sideways movement of the glider at the start of the run). Further a sportsman has the main task: to accelerate the model airplane in the quickest way, but without breaking the wing. Application in the wing structure of contemporary construction materials (carbon-fiber, kevlar) permits creation of very strong models. With such a glider a sportsman may be compelled to lower his running speed only a small amount in order to preserve the model, or he may run at his maximum speed throughout the ascent of the model on the line.

Taking these considerations into account, a mathematical model of sportsman behavior (after he reaches his nominal running speed) was developed and formalized as two first-order differential equations of the first order with nonlinearity:

$$\dot{V}_A = \begin{cases} 0 & \text{if } T \le T_{max} \\ k_R\,(T_{max} - T) & \text{if } T > T_{max} \end{cases}$$

$$\dot{x}_A = V_A$$

where x_A is the coordinate of the sportsman's movements on the surface of the earth, V_A is the velocity of the sportsman, T is line tension force, T_{max} is the maximum allowable line tension force, and k_R is a regulator coefficient which provides a desirable transitional process on T.

The initial data for the model of the sportsman are V_A and T_{max}. Characteristics of a model, line and environment are expressed through the force T.

The mathematical model reflects the following logic of sportsman behavior. First he runs with a maximum set speed. In the moment when force in the line reaches the maximum allowable, his velocity V_A decreases in a way to support this force value in the line. When the line force lowers beneath the ultimate allowable, the velocity of the sportsman returns to its set maximum.

Certainly, this mathematical model is only a simplified, schematic reflection of the real process of model acceleration on a line. It does not reflect dynamic specifics of a sportsman himself, i.e., his ability to accelerate and brake and the movements of his arm with a line. Nevertheless, personal experience of the authors testifies that this simplified model reflects the main factors influencing the start. These are the physical abilities of a sportsman and his behavior logic at acceleration of the model aircraft. The described mathematical model allows evaluation of the influence of these parameters on the start, the extent of its optimality, as well as energy loss due to limitations of a sportsman at the start.

Motion Equations of the System of Sportsman, Line, and Glider

Below, a system of differential equations is given to describe the process of acceleration of a glider model on a line by the sportsman. The designations correspond to Figs. 1–3.

$$\ddot{\sigma} = \Big\{ \cos\sigma \left(Y_g - g\left(m + \tfrac{1}{2} m_l\right)\right) - \sin\sigma\, X_g - Q_l \frac{l_Q}{l} - \frac{m_z}{l} - 2\left(M + \frac{m_l}{3}\right)\dot{\delta}\,\dot{\sigma} \Big\} \div \left\{ l \left(m + \frac{m_l}{3}\right)\right\} \quad (2)$$

$$\ddot{\delta} = \frac{1}{m}\left[(Y_g - mg)\sin\sigma + X_g\cos\sigma - m_l g\sin\sigma - k_l\,\dot{\delta} - k_o\,\delta\right] \quad (3)$$

$$\ddot{\vartheta} = \frac{1}{J_z}\left[M_z - T\, l_H \sin(\sigma - \psi)\right] \quad (4)$$

$$\ddot{x}_A = \begin{cases} 0 & \text{if } T \le T_{max} \\ k_R\,(T_{max} - T) & \text{if } T > T_{max} \end{cases} \quad (5)$$

$$T = \frac{m}{\sin\sigma}\Big(-\dot{\vartheta}\,V_x + \frac{Y_g}{m} - g - \ddot{\delta}\sin\sigma - 2\,\dot{\sigma}\,\dot{\delta}\cos\sigma - l\,(\cos\sigma\,\ddot{\sigma} - \sin\sigma\,\dot{\sigma}^2)\Big) \quad (6)$$

$$l = L + \delta.$$

Equation (2) describes the motion of the center of mass of the glider. Simultaneously it is assumed that (in the designation of Fig. 1) $|CO| = 0$, because $|AC| >> |CO|$. Equation (3) shows the tensile dynamics of the line. Equation (4) describes the angular motion of the glider in relation to its center of mass. Equation (5) describes the sportsman's behavior. Expression (6) defines the force T; this formula is indeterminate at $\sigma = 0$, which is not an obstacle for studies, as σ at the time of speeding up the glider changes from 20 to 90°.

Research

The essence of a good start of a glider model consists of following. At the run stage, with the model on the towline, the sportsman tries to impart the maximum possible velocity and to launch the model from the maximum altitude allowed by the line.

The higher the model velocity means the bigger its kinetic energy and, hence, the higher potential for climb.

After the line is released, the transformation of glider kinetic energy into potential energy (i.e., height) is governed by the programmed control of the glider stabilizer (or other effector). At this stage, the main task of the modeler is to select the stabilizer control and the moment of line release that ensures maximum height gain and transition to the steady-state glide.

The final evaluation of a glider start is the height after the transitional process is complete.

Thus, to research the launch of a glider, one must consider two different tasks:

1. Reaching the maximum velocity (full energy) when the glider is accelerated by the sportsman.

2. Searching the program of control and the moment of line release to achieve the maximum height and an acceptable transitional process.

To solve the first task, the numerical integration of the system of differential equations (2) - (5) was carried out on a computer, for various parameter values of glider, line, sportsman and initial conditions. The evaluation of the quality of the start was done on the basis of the glider velocity V_e at the moment of launch.

To solve the second task, system (1) was integrated, with initial conditions obtained by the solution of the first task. The pitch control was realized by discrete deflection of the stabilizer. Trajectory evaluation was done on the basis of the height of the glider after transition to a balanced glide.

THE STUDY OF MODEL BEHAVIOR ON A LINE

Basic Model

As a basic model for calculations a glider with the following characteristics was used: wing aspect ratio 18; arm and area of stabilizer 730 mm and 3.8 dm^2, respectively; model center of gravity 53 percent of the MAC (from the MAC leading edge); and distance between the hook and center of gravity $x_H = 18$ mm. The airfoil of the wing and stabilizer was the same as the HOFSAESS ESPADA with 2D turbulator; its characteristics are taken from Ref. [2]. The maximum allowable force in the line according to the condition of non-breakage of the model is $T_{max} = 15$ kg. The diameter of the line is $D_l = 1$ mm. The rigidity of the line is expressed in terms of ΔL in meters. It means that a 50 m line with a 5 kg load increases its length ΔL meters. For the basic model $\Delta L = 0.5$ m.

For these initial data, the stabilizer angle was calculated to be $\varphi_{HT}^{*} = -3.01°$, from the condition of a maximum duration of flight. For the stage of model acceleration on the line it was considered that the trailing edge of the stabilizer was elevated and $\varphi_{HT} = -4°$. For the mentioned basic model, the influence of sportsman speed, wind, diameter and rigidity of the line, model strength, angle φ_{HT}, and the position of the hook in relation to the C.G. were evaluated.

As a criterion for estimation of the quality of model acceleration on the line, the velocity V_e of the glider at the moment of release (at an angle σ of line inclination to the earth of 80°) was chosen, as it determines the climb potential. In cases when the tensile dynamics of the line greatly influenced height gain, a full energy H_e (energy height) of the glider was considered as a criterion as well:

$$H_e = H + \frac{V^2}{2g} = (l + \delta) \sin \sigma + \frac{V^2}{2g},$$

which takes into account, besides velocity, a height increment due to line stretch.

Fig. 5 shows time dependencies of the velocities V and V_a of a glider and a sportsman, respectively, and the force T in the line at acceleration of the basic model. It is characteristic that the greatest speed of a model airplane and force in a line are seen at angles σ = 40-50°. In this moment a sportsman is compelled to decelerate his running speed in order not to break the model. Here the force in a line reaches the maximum allowable T_{max} = 15 kg. At the end of acceleration the model velocity and the force in the line are considerably lower despite the fact that the sportsman runs at his maximum speed.

The angles of attack α, pitch ϑ, flight path angle θ, height H, and energy height H_e as a function of time t in the process of acceleration of the basic model are plotted in Figs. 6 and 7.

Velocities of Sportsman and Wind

A high glider start requires a sportsman to have good physical abilities. The extent to which these abilities influence the start is seen in Fig. 8, where dependencies of glider velocity for three values of sportsman speeds

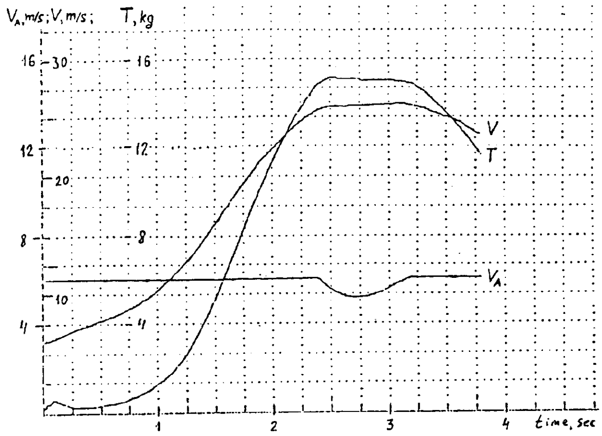

Figure 5. Glider speed V, Sportsman speed, V_A, and line tension T during tow.

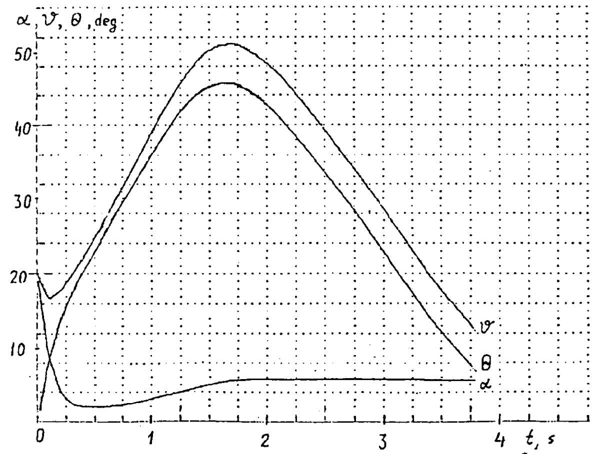

Figure 6. Flight path angle θ, pitch ϑ. and angle of attack α during tow.

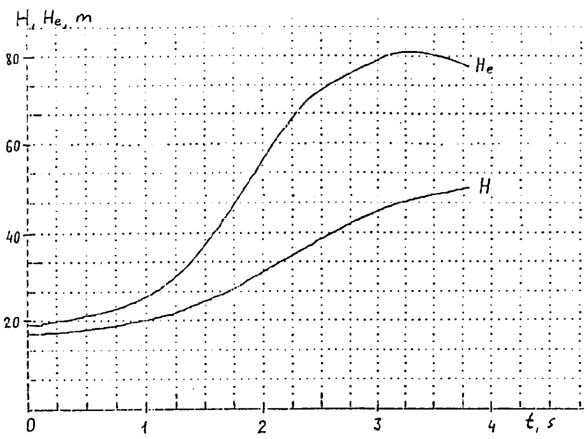

Figure 7. Height H and total energy equivalent height H_e during tow.

V_A = 5, 6, and 7 m/s are represented. Insufficient speed of a sportsman is especially strongly told at V_A = 5 m/s. In this case the force T_{max} in a line is not realized which stipulates great speed losses for a glider.

The influence of wind velocity on the start is given in Fig. 9 for wind w = 0, 1 and 3 m/s. (The sportsman's speed here is a nominal 6 m/s.) Independent of the fact that in all three cases a maximum force T_{max} in a line is realized, wind positively influences the start. First of all, it is seen that with wind intensification the glider velocity at the end of acceleration lowers to a lesser extent, and secondly, a sportsman runs with a lowered speed for a longer interval.

Diameter and Rigidity of a Line

The characteristics of acceleration are considerably influenced by such line parameters as diameter and rigidity. Fig. 10 shows that a decrease of line diameter D_l from 1 to 0.5 mm provides a gain in speed at the start of about 1.5m/s; this is because of a smaller speed decline at the end of acceleration which is determined mainly by line air drag.

The rigidity of a line has various influences on the acceleration of the model. The choice of the best rigidity is determined by whether force T_{max} is realized in the line or not. Fig. 11 shows dependencies of full energy H_e and sportsman's speed V_e for various line rigidities ΔL = 0.2, 0.5 and 2 m. It is seen from the figure that if the force T_{max} is realized in a line (ΔL = 0.2 and 0.5 m), then it is advantageous to use the more elastic line (ΔL = 0.5 m). This can be explained by two reasons. First, because of its greater elongation at the same load, and secondly, because an elastic line at the end of the acceleration returns an accumulated energy and delays the glider's speed decrease. On the other hand, if the use of a more elastic line (ΔL = 2 m) fails to realize force T_{max}, it becomes advantageous to use a line with ΔL = 0.5 or 0.2 m.

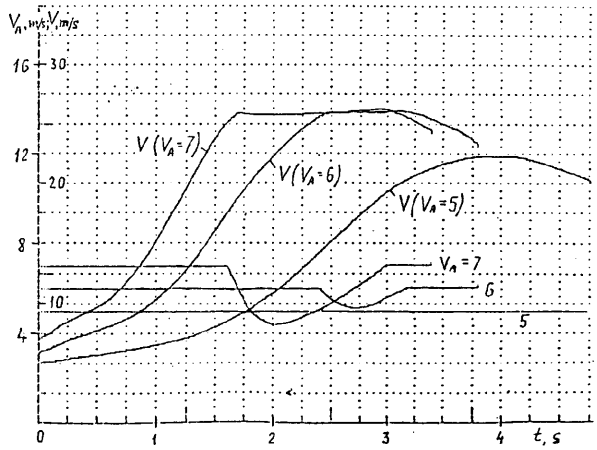

Figure 8. Effect of sportsman running at 5, 6, or 7 m/s.

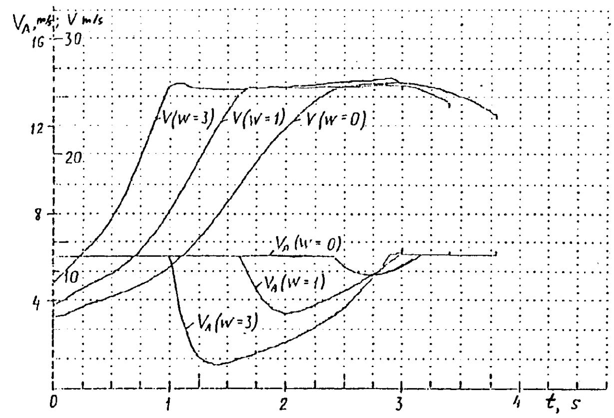

Figure 9. Effect of wind speed during tow, for sportsman running at nominal 6 m/s.

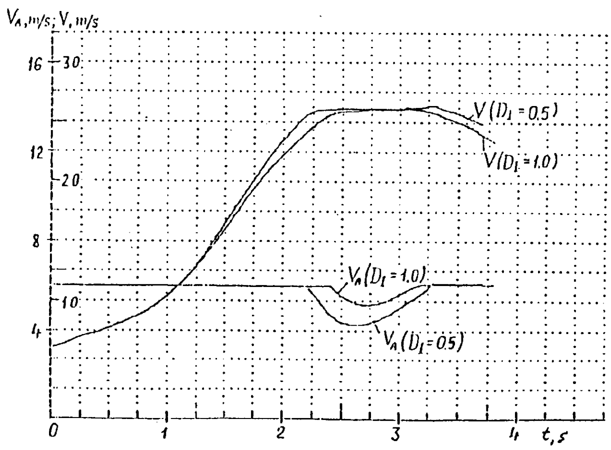

Figure 10. Effect of line diameter on glider speed and required sportsman speed.

Strength of a Glider

Fig. 12 illustrates how the breaking strength of a glider wing influences acceleration, i.e., that maximum force T_{max} in a line which a sportsman can allow without breaking the wing. Velocity graphs for a sportsman and glider are plotted for T_{max} = 10, 15, and 20 kg. It is seen how the final glider speed changes depending on T_{max}. However, further strengthening of a model expressed in an increase of T_{max} above 20 kg is senseless, as a sportsman is not able to realize it. It means that even if a sportsman runs at a maximum velocity during the entire speeding up of the glider, the force in the line will not reach T_{max}.

Stabilizer Setting Angle

Fig. 13 shows the influence of φ_{HT} for glider acceleration for the three angle values to mount a stabilizer: φ_{HT} = – 3°, – 4°, and – 5°. A conclusion can be made that for the basic model there is the best stabilizer position, φ_{HT} = – 4°. The lowering of φ_{HT} to – 5° leads to a decrease in a glider's speed because of air drag, and the increasing of φ_{HT} to – 3° hampers starting, leads to failure of force T_{max} in a line and, consequently, to the loss of glider speed.

Hook Position in Relation to Glider Center of Gravity

Fig. 14 graphs the velocities V and V_A of the basic model as a function of time, for three hook positions in relation to the center of gravity: x_H = 13, 18, and 23 mm. However, this figure does not reflect the whole design situation, but only a part, and can not be used by itself to select a hook position on a glider. In reality things are much more complicated. An optimum hook position to achieve a maximum glider speed at the start is associated with many parameters of a glider, line, and sportsman. Moreover, the influence of the value of x_H on the speed of a glider differs in different situations.

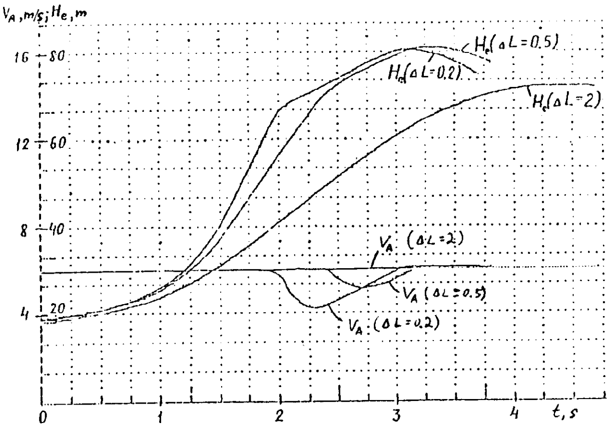

Figure 11. Effect of line elasticity on total energy and required sportsman speed.

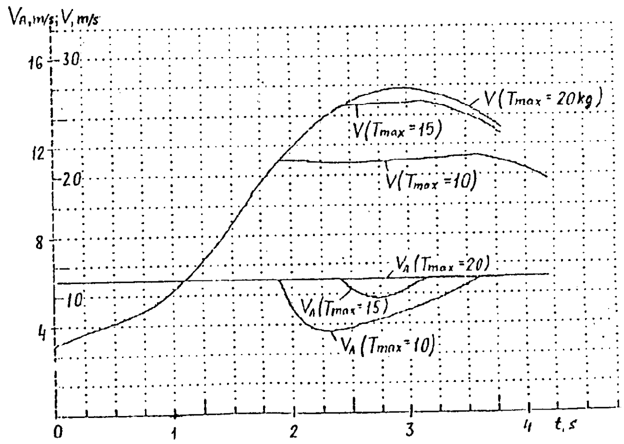

Figure 12. Effect of model strength on realizable glider speed and sportsman speed.

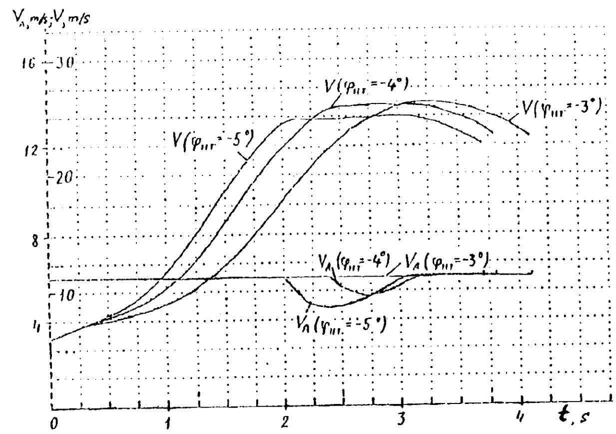

Figure 13. Effect of stablizer angle during the tow.

The authors analyzed these interactions taking account of the basic parameters influencing acceleration. Fig. 15 shows graphs of the glider speed V_e at the moment of line release as a function of hook position, x_H. The graphs are constructed for the three line types, two values of φ_{HT}, and two values of maximum allowable force T_{max} in the line. The calculations were made for a wind velocity of 1 m/s and a speed of a sportsman of 6 m/s. The velocity V_e corresponds to an angle σ = 80° between the line and the horizon. The initial data for the calculations are given in Table 1.

Fig. 15 shows with double lines those parts of the curves where the force T_{max} is realized in the towline; a single line shows those where it is not realized. An analysis of the results permits some conclusions:

1. With an increase of the hook distance x_H, the glider speed V_e increases as long as the force T_{max} in the line is realized at the time of acceleration. With further increase of hook distance x_H the speed V_e drops. Thus, an optimum distance x_H corresponds to the border of force T_{max} realization in a towline.

2. The decrease of φ_{HT} of a glider (i.e., greater elevation of the stabilizer at the trailing edge) moves the border of force T_{max} realization in a line, and, accordingly, moves the optimum value of x_H in the direction of a greater distance x_H (i.e., a more forward hook position).

3. There is an alternative in the selection of pairs of values φ_{HT} and x_H which provide approximately equal maximum speed values of a glider. To a greater φ_{HT} corresponds a lesser distance of the hook from the C.G., and vice versa. For the selection of a distance x_H one should be guided, in part, by other considerations, such as the possibility to provide good control of the glider on the towline.

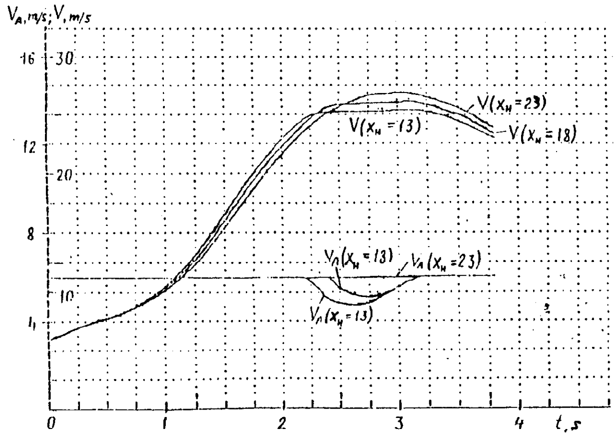

Figure 14. Effect of hook position during the tow.

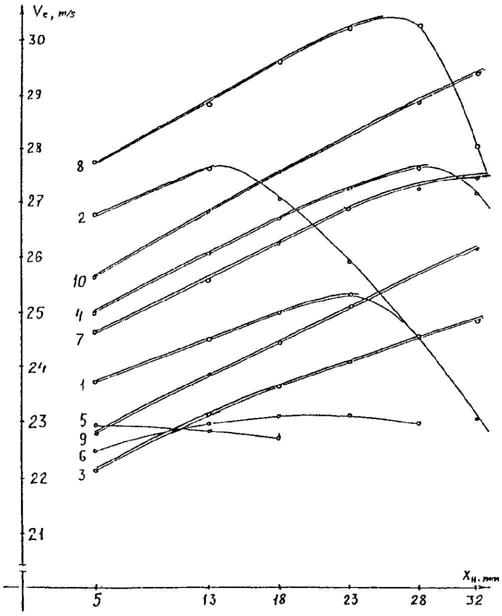

Figure 15. Effect of hook position on velocity at release for various choices of maximum tension, stabilizer angle, towline elasticity, and towline diameter.

number curve	T_{max} kg	φ_{HT} deg	ΔL m	D_1 mm
1	15	-3	0.5	1
2	20	-3	0.5	1
3	15	-4.5	0.5	1
4	20	-4.5	0.5	1
5	15	-3	2	1
6	15	-4.5	2	1
7	15	-3	0.2	0.5
8	20	-3	0.2	0.5
9	15	-4.5	0.2	0.5
10	20	-4.5	0.2	0.5

Table 1

4. The application of a more rigid line in conjunction with an opportunity to realize greater tension in the line allows the glider to reach greater speeds at the moment of towline release.

Other glider parameters include the C.G. position, arm and area of the horizontal tail, and the wing aspect ratio. They do not influence considerably the model acceleration on a line.

STUDY OF THE START WITH PITCH CONTROL

Basic Model

The performance of the start of a glider flight is determined by the characteristics of the climb and the transition to level flight. To calculate the start the earlier described basic model was used. As initial values of the phase coordinates (velocity V, angle of attack α, pitch ϑ, and height H) we used the final values computed in the task of glider acceleration on the towline.

The influence of the value of stabilizer deflection and of the moment of line release on the value of the climb and start stability were considered. For evidence, the value of stabilizer guiding deviation $\Delta\varphi_{HT}$ is given below in millimeters of the stabilizer trailing edge deviation downward (with a chord b_{HT} = 87 mm).

Figs. 16-18 show time dependencies of the velocity V, the height H, the angle of attack α, the pitch ϑ, the angular velocity ω_z of a glider and the control, i.e. the angle φ_{HT} of stabilizer position, beginning at the moment of model release. The initial data correspond to the basic model, for which acceleration on the towline was made with an initial angle of line inclination to the earth σ_0 = 20°. The value of stabilizer guiding deviation is $\Delta\varphi_{HT}$ = 10 mm. The time t_1 of the first stabilizer deviation and the duration Δt were selected in such a way

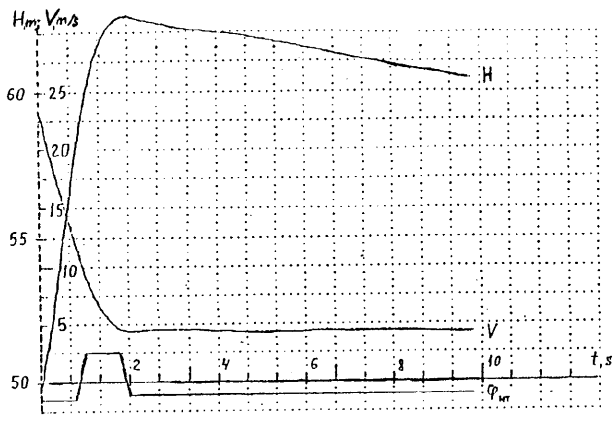

Figure 16. Glider height H, glider velocity V, and stabilizer angle φ_{HT} after launch.

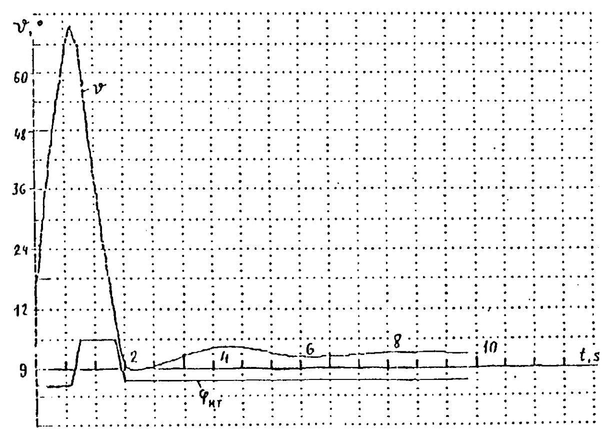

Figure 17. Glider pitch ϑ after launch.

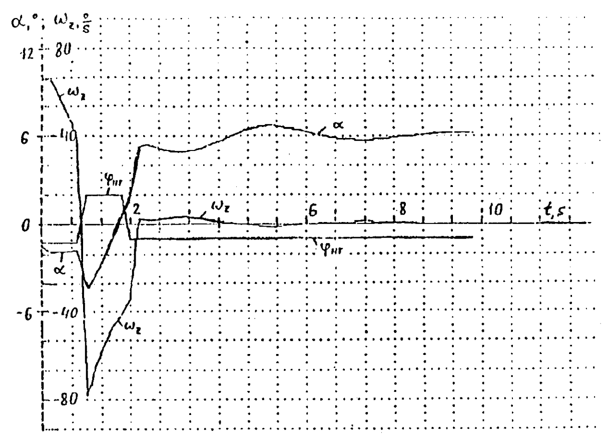

Figure 18. Glider angle of attack α and angular velocity ω_z after launch.

that all phase coordinates would have their steady-state glide values after the climb. This situation corresponds to the "ideal" trajectory, when oscillating transitional processes with loss in height are reduced to a minimum.

Value of Stabilizer Guiding Deviation

A selection of the "optimum" control (t_1, Δt) was realized for deviations of the stabilizer $\Delta\varphi_{HT}$ = 10 and 20 mm on the trailing edge. As a result, the following guiding values were determined:

for $\Delta\varphi_{HT}$ = 10 mm, t_1 = 0.9, Δt = 1.1 s;
for $\Delta\varphi_{HT}$ = 20 mm, t_1 = 1.03, Δt = 0.7 s.

Then the influence of the value of $\Delta\varphi_{HT}$ on start stability at various conditions of acceleration was estimated. For this climb trajectories were evaluated for cases when acceleration of the model was carried out from 40° rather than 20° at σ_0. The authors' experience suggests that this is a typical situation, when in a strong thermal a sportsman is compelled to start from a high circle. As a rule, there is no opportunity in this situation to accelerate the glider completely. Controls (t_1, Δt) for $\Delta\varphi_{HT}$ = 10 and 20 mm in this case were identical to those at acceleration from σ_0 = 20° and, naturally, were not optimum.

Calculation results, i.e., graphs of the height H(t), are given in Fig. 19. The start height does not essentially depend on the value of stabilizer guiding deviation in a wide range of $\Delta\varphi_{HT}$. However, it happened to be difficult to select a control (t_1, Δt) for $\Delta\varphi_{HT}$ = 20 mm, because requirements of accuracy in the setting of (t_1, Δt) increase.

At glider acceleration from σ_0 = 40°, the start height is much lower. However, non-optimality of control (t_1, Δt) in this case actually does not lead to height decrease. For the cases $\Delta\varphi_{HT}$ = 10 and 20 mm, the trajectories H(t) are very much the same.

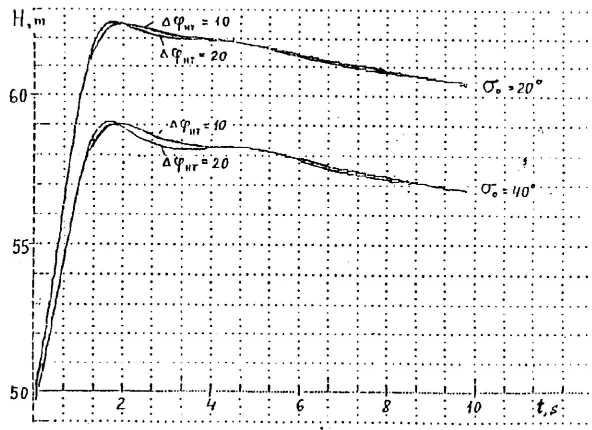

Figure 19. Effect of stabilizer deflection $\Delta\varphi_{HT}$ and initial line angle σ_0 on glider height after launch.

It is interesting to note that the results obtained produce not only a qualitative picture of the start, but also agree with practice. In particular, for $\Delta\varphi_{HT}$ = 10 mm, the mathematical model provides just the same control as that used by the authors on their gliders.

Selection of Start Moment

Due to a decrease in the glider speed at the final stage of acceleration on a towline, a question arises whether it is better to release the line a bit earlier, without lifting the glider to its maximum height, but at a greater speed. With this aim in mind, trajectories of the climb by the glider were calculated for the three points of line release according to angle σ_e = 78°, 73°, and 67°. The calculation results are given in Fig. 20. Controls (t_1, Δt) were selected to be "optimum" for each case:

for σ_e = 78°, t_1 = 0.9, Δt = 1.1 s;
for σ_e = 73°, t_1 = 0.85, Δt = 1.1 s;
for σ_e = 67°, t_1 = 0.8, Δt = 1.1 s.

Really, a glider lifts to its maximum height if the line is released at the angle $\sigma_e \cong 73°$. In relation to the control it can be said that the point of line release does not influence Δt, and that t_1 decreases with the decrease of σ_e.

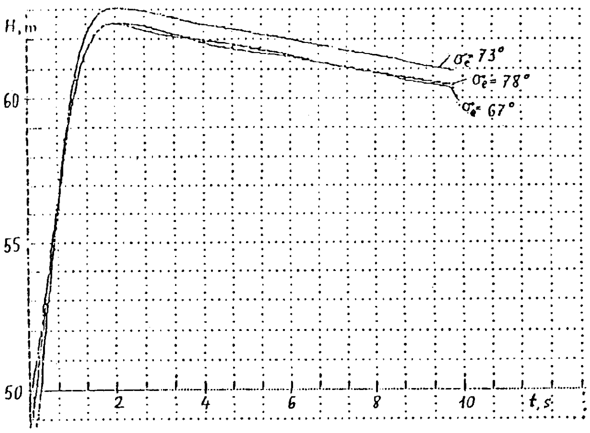

Figure 20. Effect of choice of line release angle σ_e on glider height after launch.

CONCLUSIONS

An analysis of the developed mathematical models helped achieve deeper understanding of the processes and phenomena that take place during acceleration of a glider and during the climb after release of the towline. As a criterion of acceleration efficiency, a glider velocity $V_e$at a line inclination angle of $\sigma = 80°$ was used. The climb after release was estimated under the condition of an "ideal" transitional process, which was provided by an appropriate choice of control. The results of mathematical simulations permitted us to make a number of interesting conclusions:

1. Such parameters of an aerodynamic lay-out as C.G. position, wing aspect ratio, and the area and arm of stabilizer only slightly influence the velocity V_e at the end of acceleration. This can be explained by the essential influence of aerodynamic and dynamic towline properties on the motion of a glider.

2. The velocity V_e is influenced in the most extent by the line rigidity, the sportsman's speed, the wind speed, the acceleration starting moment according to the inclination angle of the line to the horizontal, as well as such parameters as the hook position in relation to the C.G., the stabilizer setting angle, and the maximum allowable force imparted to the model under tow.

3. The velocity V_e is a nonlinear functional in the aggregate of the parameters of the glider, line and sportsman. Therefore it is difficult to give a simple answer to the question, what parameters and in what direction should changes be made to provide the most effective acceleration. An indirect evaluation of acceleration efficiency can serve to characterize the sportsman's motion and tension in the line. To the "optimum" acceleration corresponds a situation in which a sportsman moves with maximum speed during the entire acceleration, such that tension in the line at a certain moment reaches the maximum allowable value.

4. The value of stabilizer guiding deviation at the start in a range of 10 to 20 mm at the trailing edge allows one to realize the "ideal" climb trajectory.

5. To reach a maximum start height it is advisable to release a line with its inclination angle $\sigma_e \cong 70°$. In this situation a partial climb at acceleration will be compensated with the greater glider speed.

SYMBOLS

Axes

x_g, y_g – aircraft-carried normal earth axis system
x, y – body axis system
x_a, y_a – air-path axis system

Forces, Moments and Their Projections

X_g, Y_g – projections of glider aerodynamic force on normal axes x_g, y_g, respectively
X_a, Y_a – projections of glider aerodynamic force on air-path axes x_a, y_a, respectively
M_z – aerodynamic pitch moment
T – line tension force
Q_l – resultant of line air drag force
C_y, C_x – lift and drag aerodynamic coefficients, respectively, in glider body axes system
C_{ya}, C_{xa} – lift and drag aerodynamic coefficients, respectively, in air-path axes system
m_z – pitching moment coefficient
C_{xp} – profile drag coefficient
C_{xF} – fuselage drag coefficient
$m_{z\,0.25}$ – pitch moment coefficient about 0.25 wing MAC

Parameters of System

l – line length with load
L – line length without load
l_w – wing span
b_a – mean aerodynamic chord (MAC) of wing
S – wing area
S_{HT} – horizontal tail area
L_{HT} – horizontal tail arm
λ – geometrical wing aspect ratio
λ_e – effective wing aspect ratio
φ_{HT} – horizontal tail setting angle
x_T – horizontal coordinate glider center of gravity from wing MAC tip
y_T – vertical coordinate of glider center of gravity from MAC plane
J_z – glider moment of inertia in relation to body axis Oz
m – glider mass
m_l – line mass
D_l – line diameter
x_H – distance between hook (point of line fixation to glider) and center of gravity along body axis Ox
y_H – distance between hook and center of gravity along body axis Oy

Parameters of Motion and System Conditions

V – speed at the center of mass
α – angle of attack
θ – flight path angle
ϑ – pitch angle
ω_z – pitch rate (pitch angular velocity)
H – flight height
D – horizontal distance travelled by a glider
σ – angle between the direction of a towline and local horizontal plane
δ – elongation increment of a towline
g – acceleration of gravity
ρ – air density
w – wind velocity
V_e – velocity at the end of acceleration
V_A – velocity of a sportsman
x_A – distance travelled by a sportsman
σ_0 – angle σ at the beginning of acceleration
σ_e – angle σ at the end of acceleration

Indices

WHT – without horizontal tail
HT – horizontal tail
w – wing
F – fuselage
l – line
H – hook

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BIOGRAPHY

Mikhail Kochkarev was born in Moscow, Russia, in 1960. He is married and has a daughter. Since graduating from the Moscow Aviation Institute (MAI) in 1984 he has worked as an engineer in the MAI in the department of Flight Dynamics and Control of aircraft.

He began to build model aircraft at school in 1974. His main interest is F-1-A models.

In 1987 he won second place in the USSR Championships. In 1988 he won the Cup of the USSR, and second place in the European Championship. In 1988 he won third place in the USSR Championship and third place in the USSR Cup too. In 1988-1991 he was a member of the F-1-A Soviet Team.

He won the World Championships in Yugoslavia in 1991.

At the MAI he became interested in the theory of flight of free flight models and the digital computer simulation of aeromodel motion.

BIOGRAPHY

Sergei Makerov was born in 1961. He is married, has a daughter, and lives in Moscow. He finished the Moscow Aviation Institute and is working there as an engineer in the area of flight dynamics and control of aircraft.

He became interested in model aircraft in 1974 and always made F-1-A type gliders. He was champion of the USSR three times in 1983, 85 and 89 and he was vice-champion of Europe in 1986.

He won second place at the World Championships in Yugoslavia in 1991.

In 1989 he began to design computer programs for calculation of model aircraft performance, together with Mikhail Kochkarev. Their investigations are continuing.

EDITORS REMARKS

At the 1991 World Championships in Zrenjanin, Yugoslavia, the authors Mikhail Kochkarev and Sergei Makarov swept first and second place in the F-1-A glider class. Dramatic height gains on the launches of their models were key to their success. The height advantage was especially apparent during the five minute flyoff round (won by Kochkarev with Makarov and American Jim Parker tied for second) and the subsequent six minute flyoff flight to resolve the second place tie. The observation of one of us, who had the good fortune to witness these World Championship flights, is that the models of Kochkarev and Makarov gained 15 to 20 meters, twice as much as the impressive conventional launches by Parker.

Kochkarev and Markarov have rapidly become the best in F-1-A free flight gliders by using teamwork, an innovative model design incorporating a bunt launch (plans are in the *Free Flight Digest*, Dec. 1990), extensive computer modeling and simulation (as reported here), and frequent practice and competition.

The glider acceleration and launch style used by Kochkarev and Makarov at the World Championships was clearly a product of their studies reported here, with some evolution and variation of the technique. Their wings were of sufficient strength that, at least in the calm air conditions of the flyoff, they were not required to slow their sprint momentarily (as their studies show would be necessary for models with a 15 kg breaking force). Secondly, they pulled down on the line toward the end of the tow (the possibility of this was not included in their mathematical model). Consequently, they gained benefit from towing past the 73° inclination of the line from the horizontal, reported here as approximately optimal for release. These two factors may account for additional height gain achieved by the gliders of Kochkarev and Makarov beyond the 10-15 meters reported in their study.

Andrew R. Barron and Roger L. Barron,
article editors