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ON APPLICATION OF MAXIMUM PRINCIPLE TO ROCKET FLIGHT PROBLEMS

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S U M M A R Y

On the Application of the Maximum Principle to the Rocket Flight Problems

Isaev V.K, Kurianov A.I. and Sonin V.V.

The formulation and solution of the number of problems in the rocket flight is presented in general form on the basis of Pontryagin's maximum principle.

The first section considers the problem of optimum rocket flight in both uniform - constant and uniform - cylindrical gravitational fields for the cases of constant and regulated exhaust velocity. A strict conformation of the series of the results obtained earlier by some other investigators, is given, and some new statements related to optimal programming magnetude and direction of the rocket thrust.

The second section presents considerations on the techniques of numerical solution of rocket flight variational problems on digital computers.

The third section deals with the treatment of the optimum control problem of the power - and exhaust velocity - limited rocket during the interplanetary transfer. The results of numerical calculations of the bounded control effects on the parameters of transfer between the Mars and Earth orbits are discussed.

The problem of optimum transfer between the planets orbits with recovery is analysed.

An asymmetrical transfer trajectory is shown in general to be optimum.

The fourth section deals with an optimum problem of vertical limited-thrust rocket motion in the nonuniform atmosphere.

An extremal trajectory is shown be formed in general from the four arcs:

1. Maximum thrust arc or coasting arc in dependence of initial conditions.
2. Variable thrust arc.
3. Maximum thrust arc.
4. Coasting flight arc.

The first three sections of this paper present the review of the results published by Isaev and Sonin in 1961-1963 (see [8] , [10] , [15]). Paragraph 2 (Section I) deals with the materials of reference [13] written by Kuzmak and Lavidson together with one of the authors of the present paper.

The fourth section is written by Kurianov.

The maximum principle, formulated in the works of the Soviet mathematicians headed by Pontryagin, is the generalization of Weierstrass' classical variation calculus condition. The maximum principle has been widely acknowledged in recent years as a method permitting an effective treatment of optimum processes in case the control functions are bounded.

Outlined below are the results of the application of the maximum principle to some problems of optimum programming of the rocket thrust modulus and rocket thrust direction. The first section of the paper briefly relates to the main qualitative features of laws of the optimum control of constant exhaust velocity vehicles for the cases of model problems of motion in both uniform constant and uniform-cylindrical (radial) gravitational fields. Besides, some problems are considered dealing with the structure of the power-limited vehicle optimum controls in case of constraints imposed on the exhaust velocity.

The maximum principle reduces the variational problem to the boundary-value problem for the system of ordinary differential equations of the optimum object's motion.

It is important therefore to modify the available and to develop new algorithms of the boundary-value problems numerical solution by the digital computers.

These problems are considered in the second section of the present paper where the results of the numerical solution of the variational problems connected with the motion of the rocket in the Keplerian central field are analysed.

The fourth section deals with the optimum problem of vertical thrust-limited rocket motion in non-uniform atmosphere.

It is shown that the extremal trajectory consists of four successive arcs: 1/ - maximum thrust arc (or coasting arc depending on initial conditions); 2/ - variable thrust arc; 3/ - maximum thrust arc; 4/ - coasting flight arc.

I. ON SOME QUALITATIVE FEATURES OF ROCKET MOTION OPTIMUM CONTROL REGIMES

1. Rocket Optimum Motion in Uniform Constant Gravitational Field

[8,10]

1°. For the sake of simplicity, let us take the case when the effective exhaust velocity C is constant (regulated exhaust velocity case is considered in the second section). Let u and v - are speed projections on axes Ox and Oy of Cartesian frame, $m(t) = \frac{M(t)}{M(0)}$ - non-dimensional mass (related to initial value), $u_1 = \frac{P(t)}{P_{max}}$ - non-dimensional thrust (related to maximum thrust value P_{max}), φ - inclination of thrust vector to Ox axis (Fig.1).

The following constraint is imposed on the engine thrust value:

$$0 < \beta_0 \leq u_1(t) \leq 1 \qquad (1.1)$$

The equations of motion are:

$$\dot{u} = \frac{A u_1 \cos\varphi}{m}, \qquad \dot{v} = \frac{A u_1 \sin\varphi}{m} - g,$$

$$\dot{m} = -\alpha u_1, \quad \dot{x} = u, \quad \dot{y} = v,$$

where

$$A = \alpha C, \quad g = const, \quad \alpha = \frac{P_{max}}{M(0)\cdot C}.$$

Let us introduce vector $x=\{x_1,..,x_5\}=\{u(t), v(t), m(t), x(t), y(t)\}$ of state space $X=(u,v,m,x,y)$.

Statement of the problem: to determine optimum control $u=(u_1,\varphi)$ which transfers the system (1.2) from the initial fixed position $x^0=x(0)=$ $=(u^0, v^0, m^0, x^0, y^0)$ during time t = T to some set $G(x)\in X$ in such a manner that at the moment t = T the functional $S=\sum_{i=1}^{5} C_i x_i(T)$ obtains its maximum (minimum) value with constraint (1.1) imposed on the control. In this case the time T may be either free or fixed [2] and X^0 may be related to some constantly differentiable variety of space X [1].

2^0. In the general case of optimizing the arbitrary functional S, the optimum program of controlling the jet engine thrust direction versus time is expressed by:

$$tg\,\varphi(t)=\frac{p_v^0-p_y^0 t}{p_u^0-p_x^0 t}, \qquad (1.7)$$

which corresponds to the result obtained by Leitmann [4] and Lawden [5].

From Eq. (1.7) follow the results obtained by Okhotsimsky, Eneev [3], Ross [6] and Fried [7] for various types of functionals and various boundary conditions. There $p_u^0=p_u(0)$ etc. - initial values of the components of the pulse vector $p=p_u,\dots,p_y$ (i.e. of the conjugate system solution).

Each program (1.7) has a corresponding characteristic number:

$$t_0=\frac{p_u^0 p_x^0+p_v^0 p_y^0}{p_x^{0\,2}+p_y^{0\,2}}$$

Let us call the control u_1 a boundary one if the arcs of the special control in the sense of the maximum principle are not included in it; the control u_2 is special if $\beta_0<u_1<1$, $\tau_1\leq t\leq\tau_2$.

For the case of the rocket motion in the uniform constant field the following statement takes place [8].

All the S-optimum values of the control u_1 satisfy the following features:

a) control $u_1(t)$ is a boundary one;

b) optimum control consists of not more than two powered arcs (where control is accomplished at the maximum thrust regime $u_1(t)=1$);

c) if the optimum control contains two powered arcs they ajoint the boundaries of the motion interval [0, T] and the start and the end of the coasting arc are symmetric relative to the characteristic point $t = t_0$ determined by the corresponding optimum program of controlling the direction of the thrust vector $\varphi(t)$.

All the above statements generalize the known results obtained by D.E. Okhotsimsky, T.M. Eneev [3] , A. Miele, J. Capellari [9] and G. Leitmann [4] for the case of motion in the uniform constant field.

3°. The statement mentioned refers to the case of the three-dimensional optimum motion in the uniform gravitational field. In this case the thrust vector $\vec{P}(t)$ throughout the motion interval [0, T] is in some fixed plane.

This result arises from the fact that the end of the vector $p_u\vec{i} + p_v\vec{j} + p_w\vec{k}$ whose direction cosines define the angles of the thrust vector direction in space, uniformly moves along the straight line:

$$\frac{p_u - p_u^0}{p_x^0} = \frac{p_v - p_v^0}{p_y^0} = \frac{p_w - p_w^0}{p_z^0} , \qquad (1.8)$$

where $p_u^0, \ldots, p_z^0$ - initial values of pulses.

The characteristic point, in this case, is the point of the shortest distance (1.8) from the origin of coordinates (Fig.2):

$$\tilde{t}_0 = \frac{p_u^0 p_x^0 + p_v^0 p_y^0 + p_w^0 \cdot p_z^0}{p_x^{0^2} + p_y^{0^2} + p_z^{0^2}}$$

All the admissible types of optimum controls of thrust value in the uniform field are shown in Fig.3 [10] .

It should be noted in conclusion, that any problem of the optimum motion in the uniform field is reduced to quadratures which are expressed by elementary functions. Thus the variational problem is reduced to the solution of transcendental equations [8] .

2. Rocket Optimum Motion in Uniform-Radial Field

1°. Uniform-cylindrical model of the radial gravitational field is introduced into consideration in [13] .

The advantages of such a model of the field are evident in the case for which the flying range is the value of the same order as $\tilde{z}$ where $\tilde{z}$ distance from the gravity center to the middle of the cylindrical layer in which the rocket trajectory passes.

By approximating the projections of the gravitational acceleration on axes $0x$ and $0y$ (with the origin of 0 in the gravity center) with the expressions $g_x \simeq -\nu^2 x$, $g_y \simeq -\nu^2 y$ where $\nu^2 = \frac{g(\tilde{z})}{\tilde{z}} = const$, determine the optimum program of the thrust direction:

$$tg\,\varphi = \frac{\nu p_v^0 \cos\nu t - p_y^0 \sin\nu t}{\nu p_u^0 \cos\nu t - p_x^0 \sin\nu t}, \tag{1.9}$$

from which follows the periodicity of the optimum law:

$$tg\,\varphi\left(t + \frac{2\pi}{\nu}\right) = tg\,\varphi(t) .$$

2°. The optimum program of thrust modulus is boundary if

$$\vartheta = \rho + \frac{m p_m}{c} \neq 0 .$$

If the conditions

$$\rho = \sqrt{p_u^2 + p_v^2} = const, \quad \vartheta_0 = \rho_0 + \frac{m_0 p_m^0}{c} = 0 \tag{1.10}$$

take place, there can be special, in the sense of the maximum principle, optimum control $u_1(t)$ when $\beta_0 < u_1(t) < 1$.

It is important to note that the special control (if it is accomplished on the trajectory) does not conjugate with the boundary control at any arc.

Analysing the switching function ϑ (Fig.4) on the basis of the methods described in [8] , the following conclusions can be drawn: on optimum trajectories of long duration can be realized any number of decreasing powered arcs which form, except the first one, the sequence with period π/ν.

There occurs a symmetry of coasting arcs boundary points relative to time moments t_{oK} corresponding to the minimum values of $\rho=\rho_{min}$ and forming the sequence with period π/ν.

3. Optimum Motion of Space Power-Limited and Exhaust-Velocity-Limited Vehicle [15]

Let us consider the optimum motion of a space vehicle in case of constraints imposed on the control parameters (power $N=-\frac{\dot{m}c^2}{2}$ and exhaust velocity C of the jet stream). The works by Irving-Blum [12] and Leitmann [14] dealt with the problem of interplanetary flights with an engine whose jet flow maintains constant power at any exhaust velocity (Fig.5a). Leitmann showed that when a constraint

$$0 < \gamma \leq N \leq N_{max} = N_o \qquad \text{(Fig.5)}$$

is imposed on the power N, minimum transfer time flight (in uniform constant field) must be made at the upper border N = No and it is not advantageous to interrupt the engine operation [14] .

The maximum principle permits carrying out the analysis for the engine having arbitrary characteristics U_* in the plane (N,C) (Fig.5a), including the limitations imposed on the exhaust velocity C (Fig.5). It is possible to show that the optimum control will always*) pertain to the outer border Γ_* of the U_* area.

If the part of the border Γ_* aligns with the axis N = 0, coasting arcs are permitted in the optimum control.

Calculations were carried out for characteristics of the type shown in Fig.5д (or 5e which is equivalent)..

The branch of the characteristic in the range $0 \leq C \leq C_{min}$ is a curve of constant consumptions, the central - constant power; C_{max} - upper limit of regulated exhaust velocity.

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*) An exception is a fine case of the special control when the switching function $\vartheta=\rho+\frac{\rho_m m}{C}$ converts to zero in non-zero interval.

For characteristic of the type 5_A there are the following optimum control regimes: a) exhaust velocity $C = C_{min}$ (lower velocities are disadvantageous); b) variable exhaust velocity $C_{min} < C < C_{max}$; c) maximum exhaust velocity $C = C_{max}$; d) coasting motion $(N = 0)$

Some particular cases of coasting arcs realization during the motion of the vehicles with limited power have been studied by Leitmann [16] .

II. SOME PROBLEMS CONNECTED WITH DEVELOPMENT OF NUMERICAL METHOD OF BOUNDARY-VALUE PROBLEMS SOLUTION [17]

1°. It has been noted [11] , that the existing methods of the boundary-value (hence variational) problems solution are sufficiently effective only in case of the reliable first approximation. The algorithm of the boundary-value problem numerical solution used by the authors is based on Newton's method modification in which unlike the classical scheme for improving the convergence the pitch value $\Delta p^{\circ}_{K} = (\Delta p^{\circ}_{1K}, \dots, \Delta p^{\circ}_{mK})$ on K iteration is corrected in a definite way according to the values of the "missing function" φ *) calculated in a number of discrete points on the beam connecting the start and the end of K iteration in subspace of unknown initial values of pulse vector components $p^{\circ} = (p^{\circ}_{1}, \dots, p^{\circ}_{m})$.

In the convergence field $(\varphi_K \ll 1)$ the pitch value coincides with that given by Newton's classical method.

2°. Let us explain the simplest correction algorithm by the example of calculating the optimum program of controlling the pitch angle $\varphi(t)$ of the Earth satellite carrier-rocket.

The value of the true anomaly ν_0 of the stage starting point, initial conditions at the starting moment, the orbit altitude in perigee **)

$r = R + H^1$ where R - Earth radius (Fig.6), the value of the final non-dimensional mass m^1 and program of controlling the thrust magnitude

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*) $\varphi_K = 0$ when boundary conditions are satisfied.

**) It is supposed that the velocity at the end of the orbiting phase (when the velocity radial component converts to zero) is higher than the circular orbit velocity).

$u_1(t)$ are considered to be set. The engine is started at the moment t = 0 and operates at the maximum thrust regime till fuel reserve is completely burnt out (Fig.7a).

The velocity in perigee serves as a functional.

The variational problem considered is reduced to the boundary-value problem for the system:

$$\left.\begin{aligned}
&\dot{u} = -\frac{A u_1(t)}{m(t)} \cdot \frac{p_u}{\sqrt{p_u^2+p_v^2}} - \frac{\mu x}{(x^2+y^2)^{3/2}}, \\
&\dot{v} = -\frac{A u_1(t)}{m(t)} \cdot \frac{p_v}{\sqrt{p_u^2+p_v^2}} - \frac{\mu y}{(x^2+y^2)^{3/2}}, \\
&\dot{x} = u, \quad \dot{y} = v, \\
&\dot{p}_u = -p_x, \quad \dot{p}_v = -p_y, \\
&\dot{p}_x = \frac{\mu}{(x^2+y^2)^{5/2}}\left[p_u(y^2-2x^2) - 3p_v x y\right], \\
&\dot{p}_y = \frac{\mu}{(x^2+y^2)^{5/2}}\left[-3p_u x y + p_v(x^2-2y^2)\right]
\end{aligned}\right\} \qquad (2.1)$$

with boundary conditions

$$t=0, \quad u(0)=u^\circ, \quad v(0)=v^\circ, \quad x(0)=x^\circ, \quad y(0)=y^\circ; \qquad (2.2)$$

$$t=T, \quad p_u(T)=-1, \quad v(T)=0, \quad x(T)=0, \quad y(T)=z \qquad (2.3)$$

In Eqs (2.1) u, v, x, y – velocity projections and coordinates in the Cartesian frame, whose Oy axis passes through the perigee.

To determine the unknown time moment of passing through the pergiee T the following condition is used*) :

$$\widetilde{H}(T) = -\frac{\mu}{(x^2+y^2)^{3/2}}\left(p_u x + p_v y\right) + p_x u + p_y v = 0 \qquad (2.4)$$

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*) Duration of the powered arc is supposed to be $t_a = \frac{1-m^1}{\alpha} < T$.

There is a mixed four-parametric problem: to determine four unknown values ρ_u^0, ρ_v^0, ρ_x^0, ρ_y^0 the first, second and fourth conditions of (2.3) and (2.4) are used.

In this case the third condition of (2.3) is used to determine the end of integration interval. Behavior of the "missing function"

$$\varphi=\sqrt{(\rho_{ur}^1+1)^2+(\bar{v}_r^1-0)^2+\left(\frac{y_r^1}{z}-1\right)^2+(\tilde{H}^1-0)^2}$$

depending on the iterative number for one typical case is shown in Fig.5 **).

After the first step made in accordance with Newton's classical method, the indicating point (i.p.) is put in the position A (Fig.7). Increase in the error level indicates that the iterative process tends to divergence. After performing the first approach (in the direction of the beam found half a step back), we find that there is a high "peak" between the unknown minimum and point A.

Having returned another 1/4 of a step, the i.p. descends the slope of the "ravine" to the "B" position, which is located below the initial level "a". At this the first step of iteration is considered completed: the resulting curve is shown in bold type in Fig.7. Further decrease in the level is performed using Newton's classical method.

III. ON SPACE VEHICLE OPTIMUM MOTION IN RADIAL FIELD

As an example let us consider a two-dimensional problem of optimum flight between the circular orbits of Earth and Mars.

1^0. First let us touch on the problem without constraints.

Shown in Figs 8 and 9 are respectively the optimum trajectories and the plotted functional $F(T)=\int_0^T a^2 dt$ where a - jet engine acceleration, for flights at an average angular velocity equal to the angular velocity of the Earth's rotation - for the flight time T from 73 days to 1 year.

**) $\bar{v}=\frac{v}{V_{\kappa p}}$ where $V_{\kappa p}$ circular orbit velocity at an altitude of $z-R=H^1$.

At the T values approximately less than 0.21 year the optimum trajectories are fully located outside the Earth's orbit.

2^o. One can get the qualitative idea of the problem with constraints by considering a flight to Mars' orbit with a duration of T = 0.5 year.

The optimum programs of controlling the exhaust velocity with respect to time for various constraints are shown in Fig.10. The required maximum exhaust velocity without constraints is equal approximately to 2300 km/sec. Shown in Fig.11 are the values of the relative final mass $m(T) = m^1$ obtained for the case α = 10 kg/kW at the optimum power/weight ratio corresponding to the case when the value C does not reach the limits.

It is seen that the variation C_{max} of 100 km/sec to ∞ does not practically affect the value m^1 for the two above considered values $C_{min} = 0$ and $C_{min} = 20$ km/sec.

Thus, decrease in the limit of controlling the exhaust velocity from the optimum value (2300 km/sec) to $C_{max} = 50$ km/sec decreases the value of the final mass by approximately 0.5% from the initial value m^o. The effect of the lower limit (C_{min}) on the value m^1 is also slight.

Consequently, the designing of an engine adjustable within a wide range can hardly be considered expedient (at least for flights to the nearest planets of the Solar system).

3^o. Up to now we have been considering one way flights. As far as we know, optimum motions with re-entry - for low thrust engines were considered only for the cases of symmetric flights.

It is known that on the symmetric trajectories of flight ($\Psi_{Earth-Mars} = \Psi_{Mars-Earth}$, $T_{Earth-Mars} = T_{Mars-Earth}$ where Ψ and T are the angle and time of the flight respectively) tranversality conditions are satisfied, which sometimes makes us suppose that optimum trajectories of flights with re-entry belong to the class of symmetric curves.

However the latter supposition is not always true, thus the symmetric curves ensure in a general case only the local extremum.

To prove the above statement we set an example of an inter-orbital flight Earth-Mars-Earth of a 1 - year duration. A symmetric flight trajectory is shown in Fig.12, to this flight corresponds the value $\int_0^T a^2(\tau)\,d\tau$ indicated in Fig.13.

Shown in Figs 12 and 13 are an asymmetric flight and the corresponding diagram of the value $\int_0^T a^2(\tau)\,d\tau$ versus t.

It is obvious that at a symmetric optimum motion the functional value exceeds by more than 25% the corresponding value for the case of an asymmetric flight.

IV. ON OPTIMUM VERTICAL ROCKET MOTION IN NONUNIFORM ATMOSPHERE

1°. The problem of determining the optimum regimes of a rocket motion is rather thoroughly investigated in a number of references [18, 19, 20] using methods of classical variational calculation, in the main, for the case when no constraints are imposed on the thrust value.

With constraints imposed on the thrust value, this problem was considered in Ref. [20] . It was shown in it that during the ascent of the rocket the extremal consists of three arcs: the first - motion at the maximum thrust regime or with the engine cut off depending on the initial conditions, the second - motion at the variable thrust regime and, the last one - motion with the engine cut off or at the maximum thrust regime depending on the final conditions. This result does not pertain to more complicated regimes of the optimum motion and due to this it is considered particular. The application of the maximum principle to the above indicated problem permitted finding out the extremal composition in the general case.

The equations of the rocket motion in the uniform gravitational field are as follows:

$$M\frac{dV}{dt} = P_{max}\cdot u - Mg - X,$$

$$\frac{dy}{dt} = V,$$

$$\frac{dM}{dt} = -\frac{P_{max}\cdot u}{c},$$

where $X(y,V) = \frac{C_x \rho V^2}{2} S$ drag force, $\rho = \rho_0 e^{-\alpha y}$ - air density, $u(t)$ - control function changing within the interval $0 \leq u \leq 1$.

Let us introduce new variables

$$h = \alpha y, \quad M(t) = M_0 m, \quad v = \frac{V}{C}, \quad \tau = \frac{gt}{C^2}$$

Then the equations of motion are transformed into the following form:

$$\frac{dv}{d\tau} = \frac{Nu - Q}{m} - 1,$$

$$\frac{dh}{d\tau} = \frac{1}{\beta} v,$$

$$\frac{dm}{d\tau} = -Nu,$$

where

$$N = \frac{P_{max}}{M_0 g}, \qquad Q(h, v) = \frac{X}{M_0 g}, \qquad \beta = \frac{g}{\alpha c^2}.$$

Let us denote the vector $x = \{u(\tau),\ h(\tau),\ m(\tau)\}$ in the term of x.

Statement of Problem. Determine such control $u(\tau)$ $(0 \le u \le 1)$, so that the proper trajectory $x(\tau)$ expressed in equations (4.1) and originating at the moment $\tau = 0$ from the point x^0, passes at a certain moment $\tau = T$ through the point $\tilde{x}^1$ and the functional

$$S = C_v v(T) + C_h h(T) + C_m m(T)$$

would attain the maximum possible value*).

2^0. According to the maximum principle, let us introduce into the consideration the vector $p = (p_v, p_h, p_m)$ and the function

$$\begin{aligned} H &= p_h \frac{v}{\beta} + p_v \left(\frac{Nu - Q}{m} - 1 \right) - p_m Nu = \\ &= \left(\frac{p_v}{m} - p_m \right) Nu + p_h \frac{v}{\beta} - p_v \left(\frac{Q}{m} + 1 \right), \end{aligned} \tag{4.2}$$

where the variables p_h, p_v, p_m satisfy the system of equations

$$\begin{aligned} \frac{dp_h}{d\tau} &= \frac{p_v}{m} \frac{\partial Q}{\partial h}, \\ \frac{dp_v}{d\tau} &= \frac{p_v}{m} \frac{\partial Q}{\partial v} - \frac{1}{\beta} p_h, \end{aligned} \tag{4.3}$$

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*) The dimensionality of vector $\tilde{x}$ is less than that of vector x, and coefficients C_i $(i = v, h, m)$ are not equal to zero simultaneously.

$$\frac{dp_m}{d\tau} = \frac{p_v}{m} \cdot \frac{Nu - Q}{m} . \qquad (4.3)$$

Let us denote the switching function with $\tilde{\vartheta}$

$$\tilde{\vartheta} = \frac{p_v}{m} - p_m .$$

The function H has the minimum in the following cases:

1) if $\tilde{\vartheta} < 0$, then $u = 1$;
2) if $\tilde{\vartheta} > 0$, then $u = 0$;
3) if $\tilde{\vartheta} \equiv 0$, the control would be special from the point of view of the maximum principle.

3°. Let us consider the case of the special control.

Using the condition $\tilde{\vartheta} = 0$, $\tilde{\vartheta} = 0$ after integrating (4.3) we obtain

$$p_m = C_1 e^{v+\tau} ,$$

$$p_v = p_m m = C_1 m e^{v+\tau} , \qquad (4.4)$$

$$p_h = \beta \frac{p_v}{m} \left(\frac{\partial Q}{\partial v} + Q \right) = C_1 \beta \left(\frac{\partial Q}{\partial v} + Q \right) e^{v+\tau} .$$

For the sake of clarity let us analyse the case when the time is not fixed before but is determined from optimum considerations.

As the function H does not explicitly contain the time, $H \equiv 0$, the following relation takes place:

$$p_h \frac{v}{\beta} - p_v \left(\frac{Q}{m} + 1 \right) = 0 . \qquad (4.5)$$

Substituting p_h from (4.4) into (4.5), we obtain the following equation

$$v \frac{\partial Q}{\partial v} + Q (v - 1) - m = 0 \qquad (4.6)$$

connecting the instant weight of the rocket with the drag value.

Differentiating the final relation (4.6) and using the first equation of the system (4.1), we obtain the form for the optimum acceleration

$$\dot{v} = -\frac{Q + \frac{\partial Q}{\partial v} + \frac{v}{\beta}\frac{\partial^2 Q}{\partial v \partial h} + \frac{v-1}{\beta}\cdot\frac{\partial Q}{\partial h}}{Q + 2\frac{\partial Q}{\partial v} + \frac{\partial^2 Q}{\partial v^2}} . \qquad (4.7)$$

If we know the optimum acceleration we can determine in each point of the special control extremal the thrust value

$$Nu = (\dot{v}+1)\left[v\frac{\partial Q}{\partial v} + Q\cdot(v-1)\right] + Q , \qquad (4.8)$$

and, consequently, the value of the control function $u(\tau)$.

4°. Let us introduce the function

$$\omega = v\frac{\partial Q}{\partial v} + Q\,(v-1) - m .$$

The curve determined by the equation $\omega = 0$ and plotted on the planes (v, h) and (v, m) breaks each of them into two such regions L and K, that in the first region $\omega < 0$, in the other – $\omega > 0$.

On the curve $\omega = 0$ is point A (see Fig.14), in which the control $u=1$. Below this point the curve $\omega = 0$ corresponds to the special control regimes $(u<1)$. Above point A the special control regimes are not realized.

Further on we shall confine ourselves to the consideration of the most complicated extremals. For this purpose let us draw from point A to the left a curve corresponding to the regime $u=1$ and to the right – a curve $u=0$. The first curve in region L separates subregion L_1, the other in region K – subregion K_1. As it is known [20], if the initial point x^0 is in subregion L_1, the motion begins from the regime $u=1$, and if it is located in subregion K_1, the motion will be accomplished at zero thrust arc $(u=0)$.

For the sake of clarity let the final point be located in region L.

Now let us use the switching function $\hat{\vartheta}$ to construct line $\hat{\vartheta}=0$ $(\vartheta \neq 0)$ originating from point A. The coordinates of this line are determined by the equation

$$\tilde{v} = e^{\int_{\tau_2}^{\tau_3} \frac{N}{v} d\tau} \cdot \int_{\tau_2}^{\tau_3} \frac{p_v \omega}{v m^2} \cdot e^{-\int_{\tau_2}^{\tau_3} \frac{N}{v} d\tau} \cdot d\tau = 0,$$

where τ_2 - corresponds to the point on the curve $\omega = 0$,

τ_3 - corresponds to the point on the switching line.

Let us consider the possible optimum flight regimes:

1. If $m(\tau_3) > m_A$ (See Fig.15), the extremal consists of three arcs. This case is investigated in Ref. [20].

2. If $m(\tau_3) < m_A$, the extremal will consists of four arcs: the first - the regime $u = 1$ or $u = 0$ depending on the initial conditions; the second - motion along the special control trajectory till a certain moment $\tau_2 < \tau_A$ (where τ_A - time of motion to point A, if the process continued along the special control trajectory); the third - maximum thrust arc $(u = 1)$ till the moment τ_3 when $m(\tau_3) = m(T)$; the fourth - coasting flight $(u = 0)$.

An example of such an extremal is shown in Figs 16 and 17. The thrust Nu and the switching function versus the flight time are shown in Fig.18.

When the initial point is in region K_2 and the final - in region L_2, it can be shown by similar considerations that the extremal consists of three arcs. The only powered arc is in the middle and control on it is boundary $(u = 1)$ which also distinguishes the above optimum regime from the regimes considered before [20].

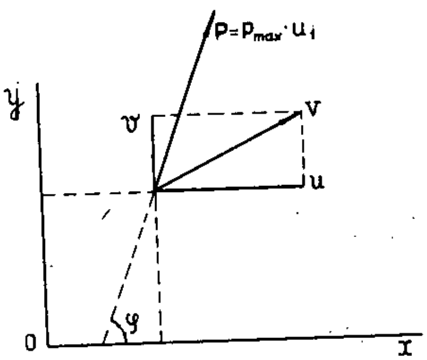

FIG. 1

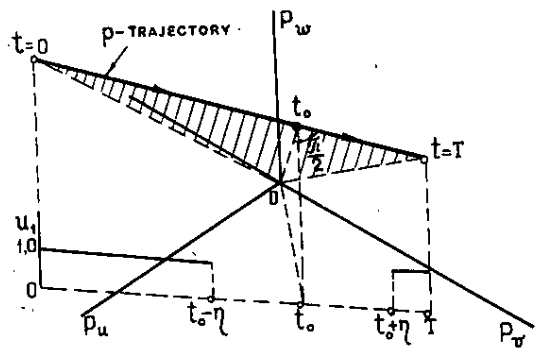

FIG. 2

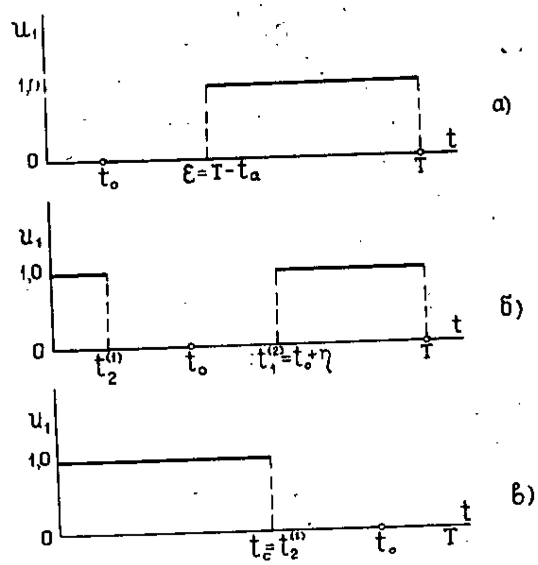

FIG. 3

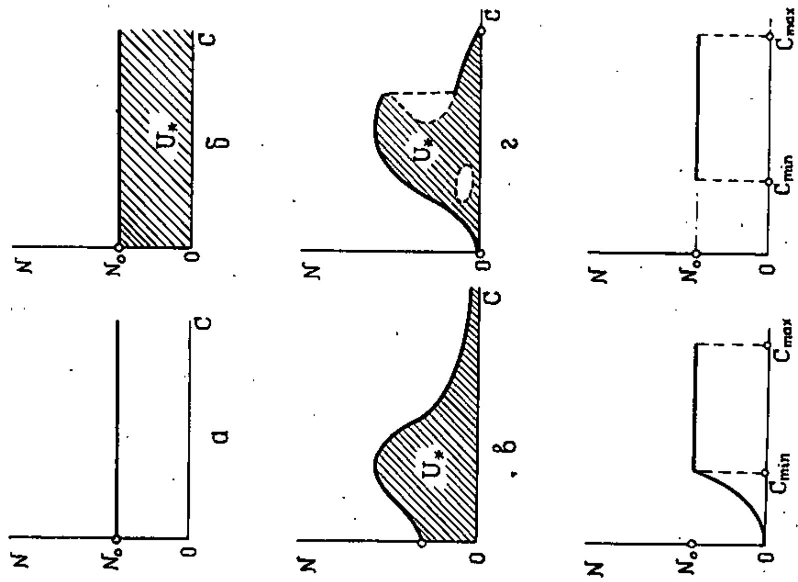

Fig. 5

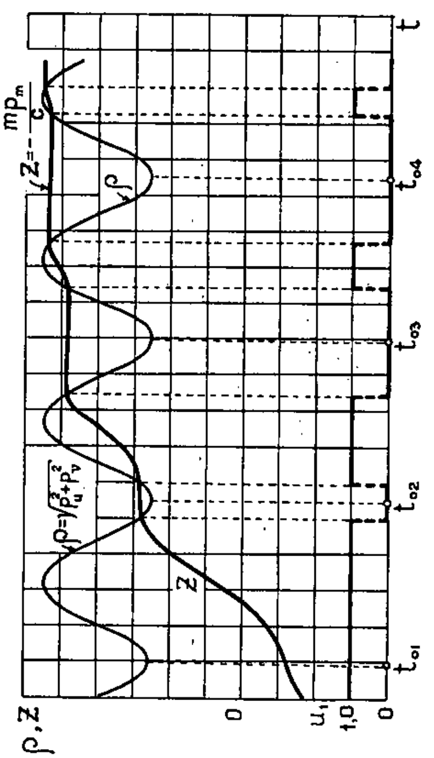

Fig. 4

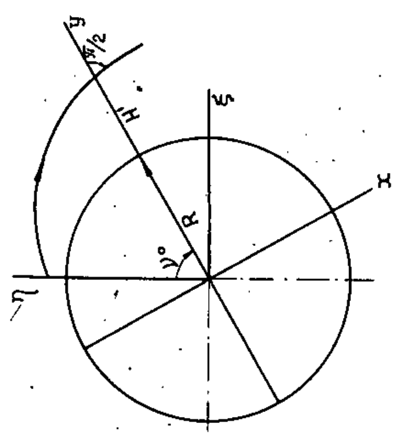

Fig. 6

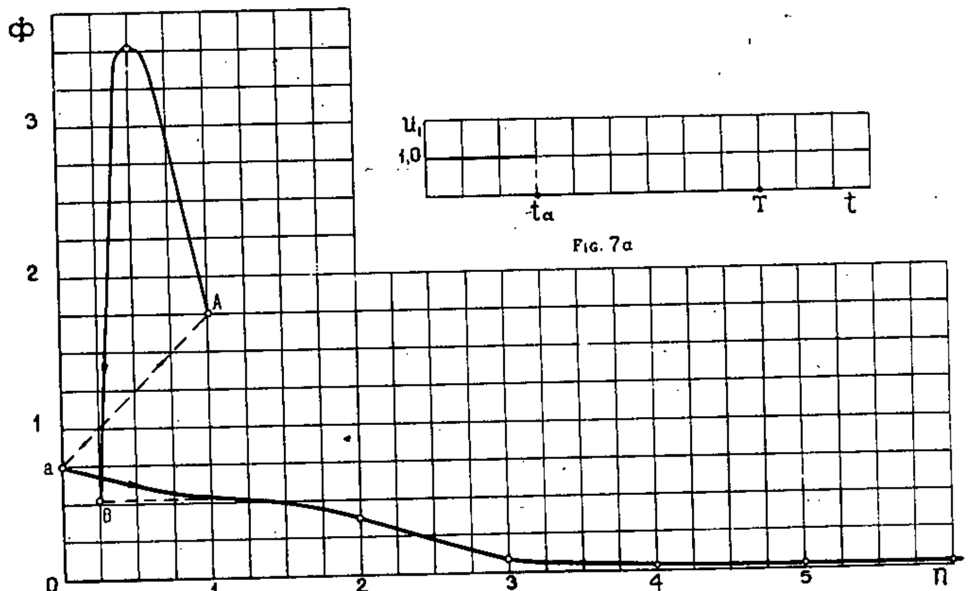

FIG. 7a

FIG. 7

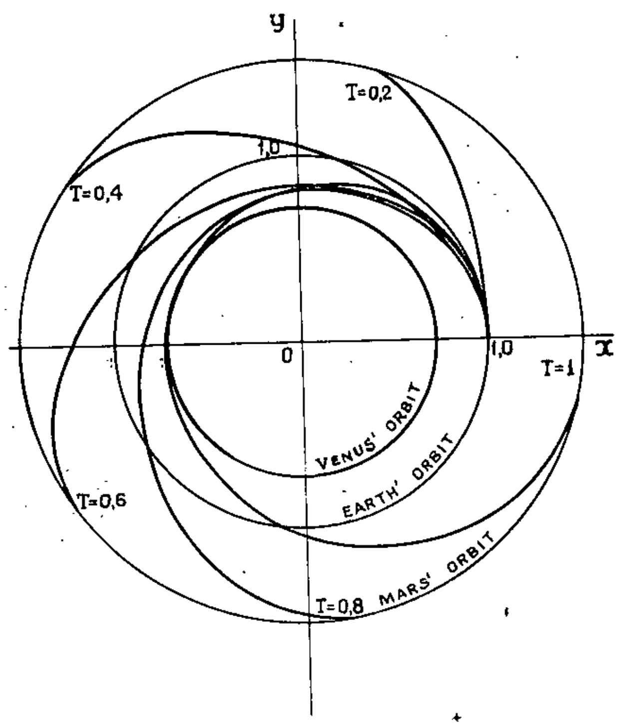

FIG. 8

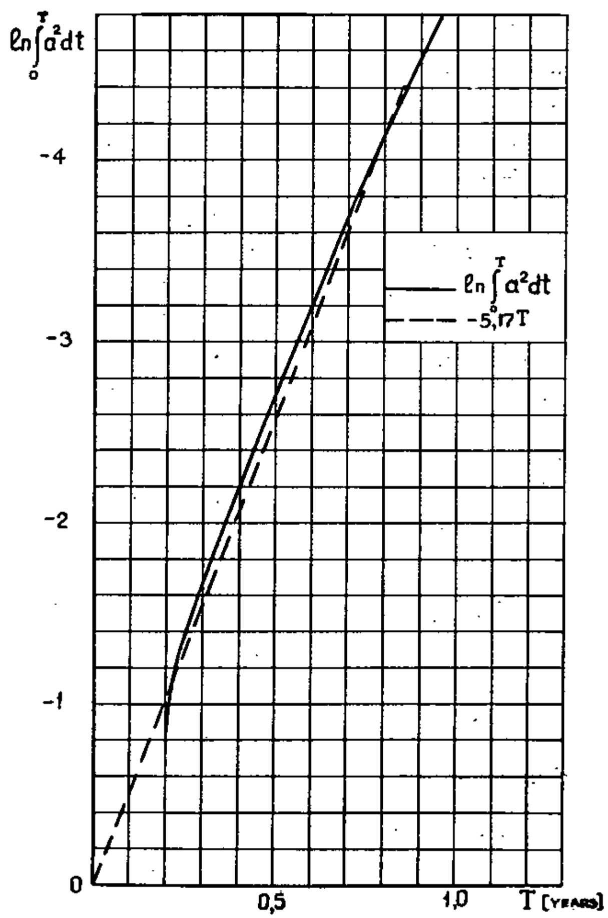

Fig. 9

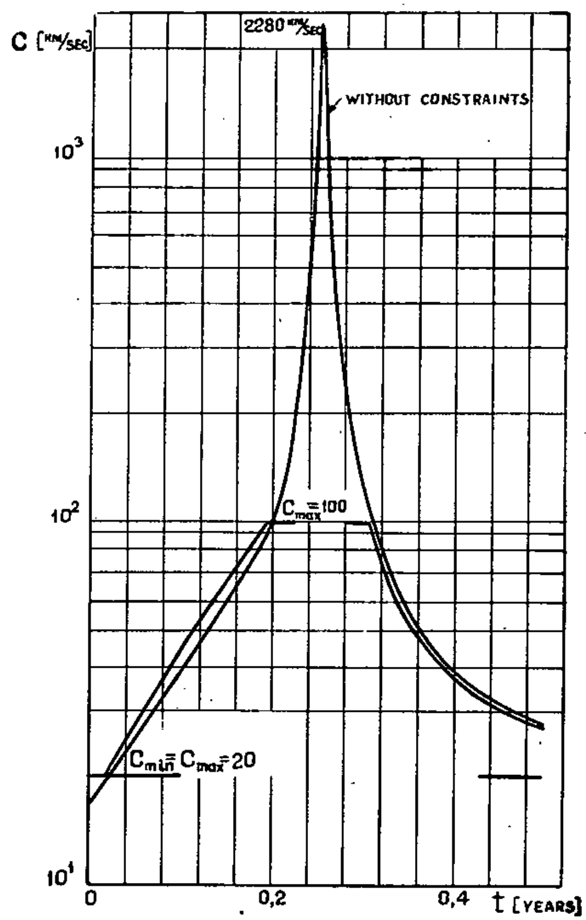

Fig. 10

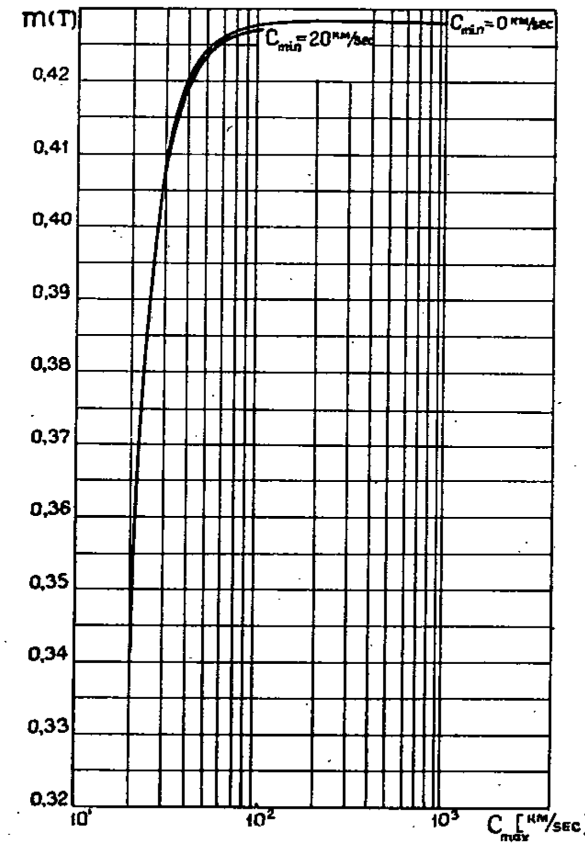

Fig. 11

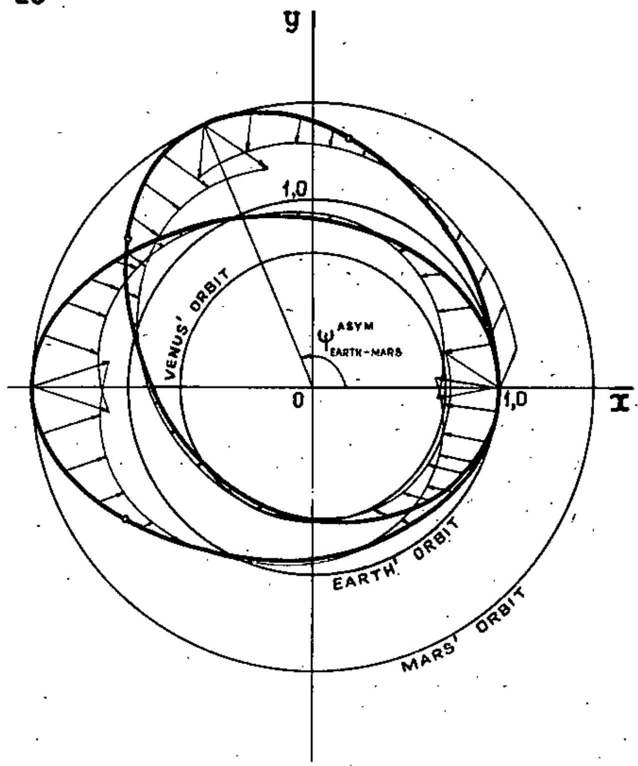

Fig. 12

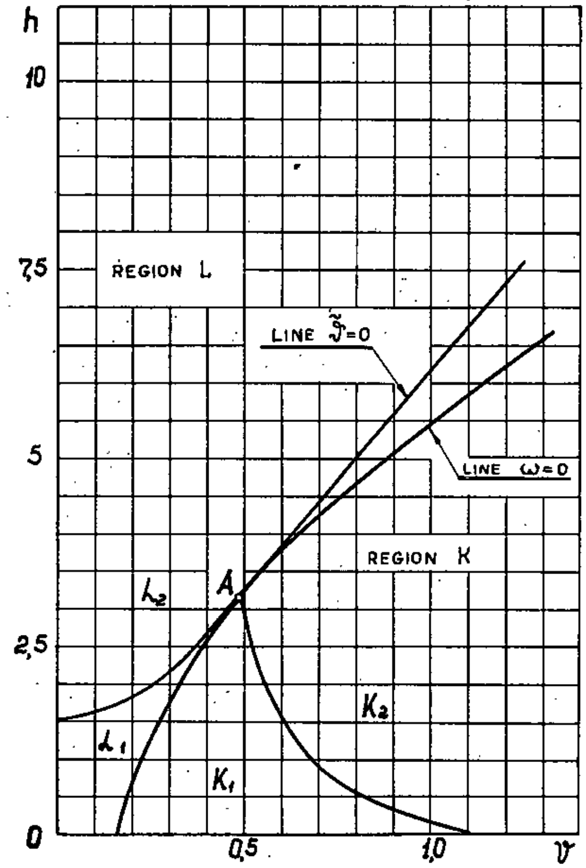

Fig. 14

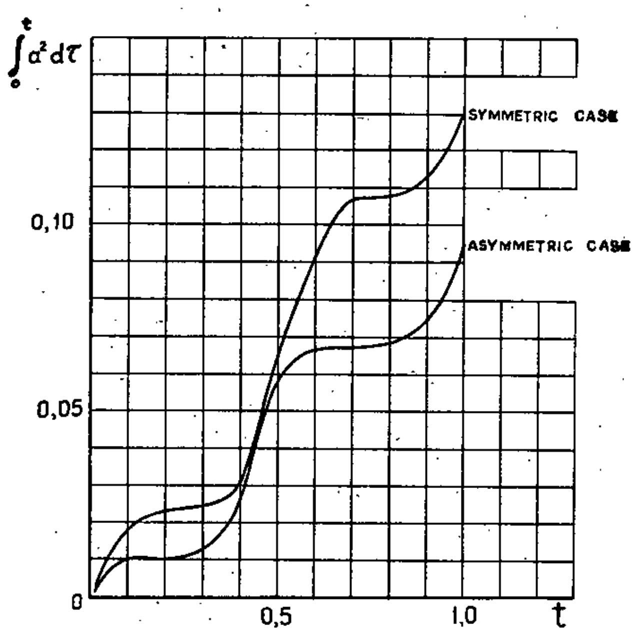

Fig. 13

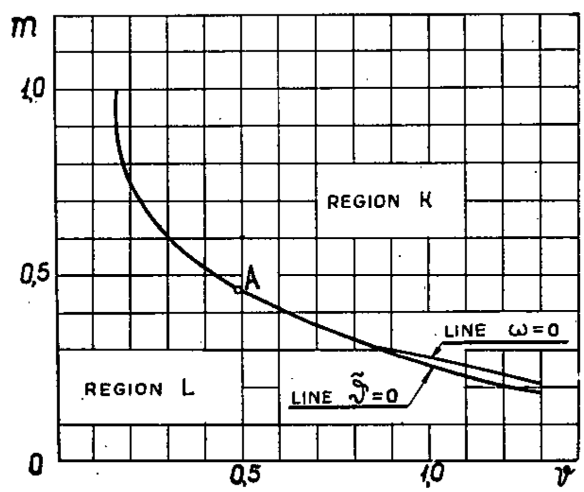

Fig. 15

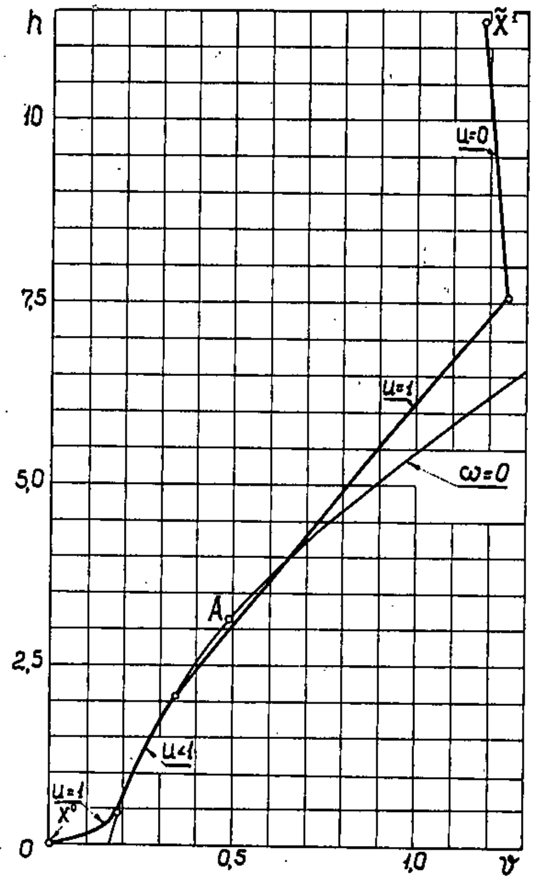

FIG. 16

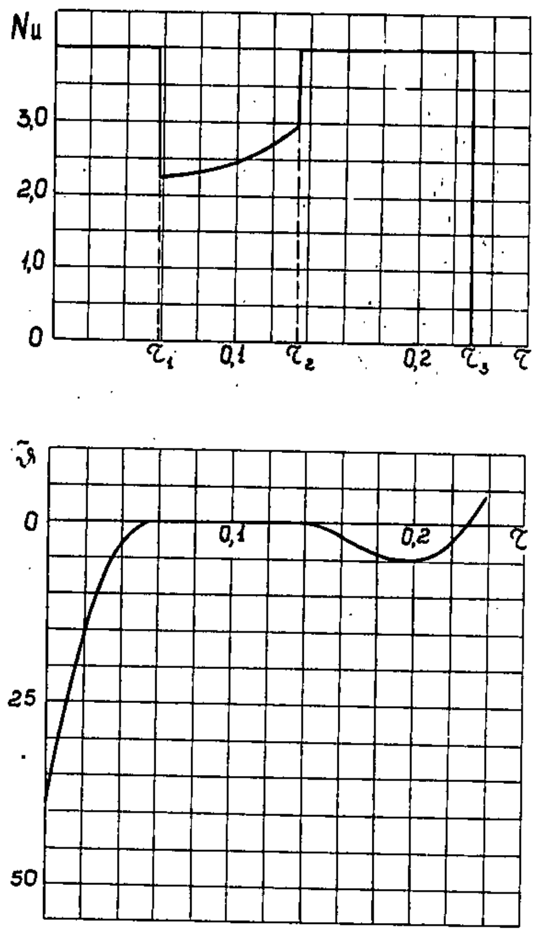

FIG. 18

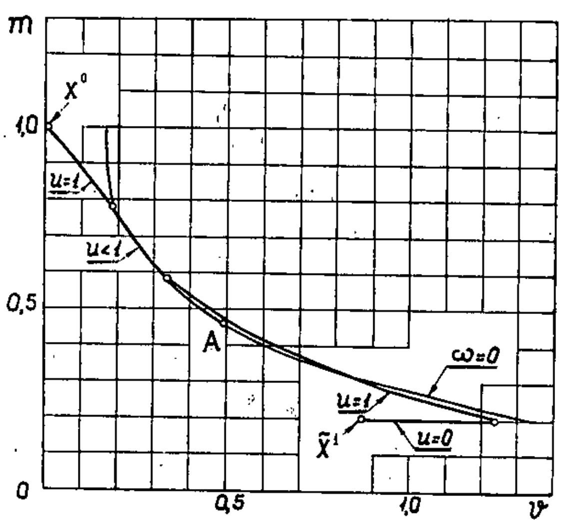

FIG. 17

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APPLICATION OF THE ASYMPTOTIC METHODS TO SOME PROBLEMS OF THE RE-ENTRY VEHICLES DYNAMICS

1963

The principal attention is paid to the non-linear problem of investigation of the free motion of the axisymmetrical bodies about mass center when they cross the atmosphere. Low parameters of the motion equations are found and the technique of the determination of asymptotic solution is described. The techniques of the solution are based on the fact that the problem is close to the Lagrange case of the solid body motion problem.

A trajectory problem of the atmospheric motion of the vehicle with a high positive lift-drag ratio known in literature as a problem of skip motion of vehicle is also analysed. And finally brief considerations are given to the accomplishment of a more rapid numerical integration of the motion equations when studying the motion approaching the Keplerian one.

1. First, consider a problem of motion of the axisymmetrical bodies about the centre of mass when they cross the atmosphere. The complete set of equations of the motion of a flying body, being reduced to a nondimensional form, is written in the form:

$$\frac{d\vec{Q}}{dt} = \vec{M}, \qquad \frac{d\vec{K}}{dt} = \varepsilon \vec{\mathcal{F}}, \qquad \frac{d\vec{z}}{dt} = \varepsilon \vec{V}, \qquad (1.1)$$

where $\vec{Q}, \vec{K}, \vec{z}$ - nondimensional kinetic moment, momentum and radius vector of the centre of mass of the body, respectively,

$\vec{M}, \vec{\mathcal{F}}, \vec{V}$ - nondimensional moment of forces, force acting on the flying body, and its velocity, respectively,

t - time related to the time interval characteristic of motion of the vehicle about the centre of mass.

In term of ε is indicated here a ratio of the time interval characteristic of the body motion about the centre of mass, to the time interval characteristic of motion of the centre of mass of a vehicle. Evaluation of this ratio shows that along almost the whole part of the atmosphere path, except for a small phase of it, directly adjoining the atmosphere boundary this ratio is a value of order $\sqrt{\frac{L}{\Delta r}}$, where L is a specific size of the body and Δr is a section of the path along which density changes several times. Since $L \approx 1$ m. and $\Delta r \approx 10^4$ m., then $\varepsilon \approx 10^{-2}$ and, therefore, along almost the whole path the equations of motion of the body in the atmosphere have a low parameter. Along a small phase of the path ("transition phase") directly adjoining the atmosphere boundary the specific velocity of the vehicle rotation about the centre of mass is still a value of order Ω_o - the velocity of the vehicle rotation beyond the atmosphere, and the indicated evaluation of ε is not valid. Along this path phase $\varepsilon \approx \frac{\lambda V \sin\theta}{\Omega_o}$ where V and θ are velocity and path angle, and λ is an exponent factor in the equation of density. Therefore, the asymptotic method may be used here only for rather large values of Ω_o and the solutions of some model equations should be used to study the motion along the path "transition phase" at small values of Ω_o Below we shall confine ourselves to consideration of two rather important cases: a case when the path profile and value Ω_o are such that ε is small along the whole flight path of the body, and a case when this condition is not feasible, but the initial conditions are such that along the whole flight path the angle of attack may be considered small.

a) In spite of the fact that the asymptotic solutions determination techniques which will be described below are applicable to the complete equations of motion, for the sake of clarity we shall confine ourselves to the study of the body motion about the centre of mass at a preset trajectory of the centre of mass. This supposition essentially simplifies the problem and at the same time in most cases does not result in any noticeable errors, since changes in the aerodynamic forces resulting from a change in the angle of attack occur most frequently at high altitudes where, due to a low air density, their effect is negligible, and in lower layers of the atmosphere the angles of attack of the body affected by the aerodynamic moment decrease so that changes in the aerodynamic forces associated with them become negligible. Under such an approximation, due to the fact that Equations (1.1) contain low parameter ε , the path parameters of the centre of mass of the vehicle may be considered a function of "slow" time $\tau = \varepsilon t$.

The motion of the axisymmetrical body is conveniently related to Resal's system of axes shown in Fig.1. In this case, since the damping moments may be considered low and the change in the velocity of the path angle with respect to the velocity of rotation of the body about the centre of mass may be neglected, the set of equations of motion of the axisymmetrical body about the centre of mass can be written in the form (see [1]):

$$\frac{d^2\alpha}{dt^2} - \lambda^2 \sin\alpha\cos\alpha + z\lambda\sin\alpha + M(\tau,\alpha) + \varepsilon f_z(\tau,\alpha)\frac{d\alpha}{dt} = 0, \qquad (1.2)$$

$$\frac{d\lambda}{dt} + \frac{(2\lambda\cos\alpha - z)}{\sin\alpha}\frac{d\alpha}{dt} + \varepsilon f_y(\tau,\alpha)\lambda = 0,$$

$$\frac{dz}{dt} + \varepsilon f_x(\tau,\alpha) z = 0,$$

where

$$z = \frac{\mathcal{J}_x \omega_x}{\mathcal{J}_z}; \qquad M = -\frac{M_z(\tau,\alpha)}{\mathcal{J}_z}; \qquad f_x = -\frac{M_x^{\omega_x}(\tau,\alpha)}{\mathcal{J}_x};$$

$$f_y = -\frac{M_y^{\omega_y}(\tau,\alpha)}{\mathcal{J}_z}; \qquad f_z = -\frac{M_z^{\omega_z}(\tau,\alpha)}{\mathcal{J}_z}; \qquad \tau = \varepsilon t;$$

α - spatial angle of attack;

λ - velocity of rotation with respect to the velocity vector of the plane passing through the vehicle roll axis and velocity vector;

M_z- restoring moment;

$M_x^{\omega_x}$, $M_y^{\omega_y}$, $M_z^{\omega_z}$ - rotating variables.

The equations of motion in Form (1.2) are the set of equations which approximates to the equations of the axisymmetrical solid body motion in the Lagrange case. However, the calculation of the asymptotic solutions of these equations in such a form involves considerable technical difficulties. These difficulties can be essentially reduced if this set of equations is reduced to such a form that at $\varepsilon = 0$ it is changed to one equation for angle of attack. As it is found to do so it is sufficient to introduce new unknown G instead of λ

$$G = \lambda\sin^2\alpha + z\cos\alpha, \qquad (1.3)$$

which is a projection of the kinetic moment vector on the velocity vector and divided by $\mathcal{J}_z$. After such a substitution the set of Equations (1.2) is reduced to the form:

$$\frac{d^2\alpha}{dt^2} + M_\Sigma(\tau, z, G, \alpha) + \varepsilon f_z(\tau,\alpha)\frac{d\alpha}{dt} = 0, \qquad (1.4)$$

$$\frac{dG}{dt} + \varepsilon \{ f_y(\tau,\alpha) G + [f_x(\tau,\alpha) - f_y(\tau,\alpha)] z\cos\alpha \} = 0,$$

$$\frac{dz}{dt} + \varepsilon f_x(\tau,\alpha) z = 0,$$

where $M_\Sigma = \frac{\partial \Phi}{\partial \alpha}$, $\Phi = \frac{1}{2}\left(\frac{G - z\cos\alpha}{\sin\alpha}\right)^2 + \int_0^\alpha M(\tau,\alpha)\,d\alpha$. (1.5)

In recent years in the Soviet Union great attention has been paid to development of the techniques for determination of the asymptotic solutions of the equations of such a form [2-8]. This paper is based on the technique developed in [5],[6] and [9]. The principal items of the technique are described below.

It is seen from the equations of motion in Form (1.4) that at $\varepsilon = 0$ and M_Σ independent of τ the motion is a single-frequency oscillatory process with time-invariable characteristics. At ε different from zero the motion is also a single-frequency oscillatory process with amplitude, frequency, etc. slowly changing in time. Therefore, it is advisable to look for a solution to Equations (1.4) as a function of two variables: slow time τ, which defines a change in amplitude, frequency, etc., and ω - oscillations phase, regarding the equations relating τ and ω to time

$$\frac{d\tau}{dt} = \varepsilon, \qquad \frac{d\omega}{dt} = \varphi(\tau), \tag{1.6}$$

where $\varphi(\tau)$ - instantaneous frequency of oscillations which is to be found.

If any of the unknown of the set of Equations (1.4) is given in term of y, then in conformity with the mentioned above the following equations may be written:

$$y = y(\tau,\omega), \qquad \frac{dy}{dt} = \frac{\partial y}{\partial \omega}\varphi(\tau) + \frac{\partial y}{\partial \tau}\varepsilon, \tag{1.7}$$

$$\frac{d^2y}{dt^2} = \frac{\partial^2 y}{\partial \omega^2}\varphi^2(\tau) + \varepsilon\left[2\frac{\partial^2 y}{\partial\omega\,\partial\tau}\varphi(\tau) + \frac{\partial y}{\partial\omega}\varphi'(\tau)\right] + \varepsilon^2\frac{\partial^2 y}{\partial\tau^2}$$

Hence it follows that representation of the solutions as a function of two variables permits separating terms of different order from the expressions of derivatives which essentially simplifies the analysis and solution of the resulting equations. With (1.7) considered, it is seen from Equations (1.4) that for determining the principal terms of the asymptotic expansion suppose

$$\alpha = \alpha_0(\tau,\omega) + \varepsilon\alpha_1(\tau,\omega)\ ; \qquad z = z_0(\tau) + \varepsilon z_1(\tau,\omega);$$
$$G = G_0(\tau) + \varepsilon G_1(\tau,\omega)\ ; \qquad \varphi = \varphi_0(\tau) + \varepsilon\varphi_1(\tau); \qquad (1.8)$$

where the functions $G_0(\tau), z_0(\tau), \varphi_0(\tau)$ and $\varphi_1(\tau)$ are to be determined, and $\alpha_0(\tau,\omega)$ is the solution of the equation which is called a "reference equation":

$$\varphi_0^2(\tau)\frac{\partial^2\alpha_0}{\partial\omega^2} + M_z[\tau, z_0(\tau), G_0(\tau), \alpha_0] = 0. \qquad (1.9)$$

Besides the four arbitrary functions given the solution of the "reference equation" also depends on function $\omega^*(\tau)$ which is additive to ω and on energy of system $E(\tau)$. All these six arbitrary functions should be determined so that functions α_0, z_0 and G_0, where τ and ω are expressed in term of t of by (1.6), satisfy the initial set of equations with an accuracy up to the terms of order ε at time interval $0 \le t \le \tau_0/\varepsilon$ having a great number of oscillations.

Substitution of Equations (1.6) into Equations (1.4) and analysis of the resulting relationships show that this condition can be satisfied if we suppose $\omega^*(\tau) = 0$ and determine the remaining arbitrary functions, so that Functions (1.8) are periodic with respect to variable ω with the period independent of τ.

The condition that function $\alpha_0(\tau,\omega)$ period is independent of τ with respect to ω permits determining one of these functions and the remaining four conditions are obtained proceeding from the requirements for periodicity of the functions $\alpha_1(\tau,\omega)$, $G_1(\tau,\omega)$ and $z_1(\tau,\omega)$ and have the following form:

$$\left[\varphi_0\int_0^{T_\omega/2}\left(\frac{\partial\alpha_0}{\partial\omega}\right)^2 d\omega\right]' + \varphi_0\int_0^{T_\omega/2} f_z\left(\frac{\partial\alpha_0}{\partial\omega}\right)^2 d\omega - \int_0^{T_\omega/2}\left(\frac{\partial\varphi}{\partial G}\frac{\partial G_1}{\partial\omega} + \frac{\partial\varphi}{\partial z}\frac{\partial z_1}{\partial\omega}\right)d\omega = 0, \quad (1.10)$$

$$G_0' + \left[\frac{2}{T_\omega}\int_0^{T_\omega/2} f_y\, d\omega\right] G_0 + \left[\frac{2}{T_\omega}\int_0^{T_\omega/2} (f_x - f_y)\cos\alpha_0\, d\omega\right] z_0 = 0,$$

$$z_0' + \left[\frac{2}{T_\omega}\int_0^{T_\omega/2} f_x\, d\omega\right] z_0 = 0\ ; \qquad \varphi_1 = 0;$$

where

$$\frac{\partial G_1}{\partial \omega} = -\frac{1}{\varphi_0}\left\{G_0' + f_y G_0 + (f_x - f_y)\cos\alpha_0 z_0\right\},$$

$$\frac{\partial z_1}{\partial \omega} = -\frac{1}{\varphi_0}(z_0' + f_x z_0).$$

Differentiation with respect to τ is indicated in (1.10) with an accent and the period of function $\alpha_0(\tau, \omega)$ with respect to ω is given in term of T_ω. The first condition out of these conditions of periodicity is an energetic relationship: the first term in it is an integral change rate with respect to doubled kinetic energy and the rest of the terms represent the work of disturbance moments. The last two equations in (1.8) are none other than a result of half-cycle oscillations averaging of the last two equations in (1.3). It is not difficult to make conditions of periodicity also for the complete set of Equations (1.1), since after introducing new unknown G (see 1.3) it assumes the same form as the set of Equations (1.4).

When using the asymptotic solutions see that the instanteneous frequency of oscillations φ_0 is not set to zero, otherwise the specific time ratio will not be a small value at some, though short, time interval. A detailed study of this problem has shown that in cases when φ_0 is set to zero at some $t = t_*$, for some discrete values of the initial conditions the precise solutions may have peculiarities which are not considered in the asymptotic solutions. But for the most of the initial conditions the asymptotic solutions give the proper results.

In the general case the system of periodicity of Conditions (1.10) should be integrated numerically. But numerical integration of this system requires machine-calculated time $1/\varepsilon$ times less than integration of the initial set of Equations (1.4) since its solutions do not contain high-frequency components. If it is considered that damping substantially affects the motion only in the lower layers of the atmosphere, where the angles of attack may be regarded small this system can be integrated in the closed form.

Neglecting damping at high altitudes, from (1.10) we have:

$$G_o = const.; \quad \tau_o = const; \quad \varphi_o \int_0^{T\omega/2} \left(\frac{\partial \alpha_o}{\partial \omega}\right)^2 d\omega = const. \qquad (1.11)$$

While at low altitudes due to small angles of attack functions f_x, f_y and f_z may be considered independent of α, $\cos\alpha = 1$ and besides, for axisymmetrical vehicle, assume $f_y = f_z$. Considering the above given assumptions, Equations (1.10) may be replaced by the following:

$$G_o(\tau) = \tau_o(\tau) + const\, e^{-\int f_z d\tau}; \quad \tau_o(\tau) = const.\, e^{-\int f_x d\tau}; \qquad (1.12)$$

$$\varphi_o(\tau) \int_0^{T\omega/2} \left(\frac{\partial \alpha_o}{\partial \omega}\right)^2 d\omega = Const.\, e^{-\int f_z d\tau}$$

The motion can be studied in great detail at $M(\tau,\alpha) = g(\tau)\sin\alpha\, (g(\tau) > 0)$ since in this case, the solution of "reference equation" (1.9) can be expressed by Jacobian elliptic functions.

$$\cos\alpha = A(\tau) + B(\tau)\, sn^2[K(\nu(\tau))\omega,\ \nu(\tau)], \qquad (1.13)$$

where $A(\tau)$, $B(\tau)$ and $\nu(\tau)$ are the functions to be determined.

Index "0" denoting the asymptotic solutions will be sometimes omitted here and further. Let's briefly dwell on two extreme cases: a planar case and a case when the axis of the body moving in the atmosphere describes a cone round the velocity vector with cone angle changing slowly. In these cases a rather full idea of the change in the vehicle angle of attack can be obtained by referring to the charts given in Figs 2 and 3:

Fig.2 shows the dependence of the amplitude of the oscillations of angle of attack for the planar case on the aerodynamic "stiffness" $g(\tau)$ and "damping" $f_z(\tau)$ (D - arbitrary constant), and Fig.3 shows the dependence on the same values of angle of attack of the vehicle for the second extreme case. The values of τ and α are given in Fig.3 in terms of τ_o and α_o for the re-entry case, where $g(\tau) = 0$. Note that the second extreme case is realized in the case of a body re-entering the atmosphere and stabilized beyond the atmosphere by rotating about the roll axis. It is well seen from the charts in Figs 2 and 3 that with increase in $g(\tau)$ which corresponds to the increase in dynamic pressure, the vehicle approaches a stable balanced position.

Let's relate then the parameters of motion at the initial moment and the parameters of motion in the lower layers of the atmosphere for the re-entry case.

As it is apparent from [1], [12], when approaching the atmosphere the axis of the axisymmetrical vehicle describes a circular cone (precesses) relative to the kinetic moment vector $\vec{Q}_0$ which is unchanged beyond the atmosphere. In conformity with this preset the vehicle motion, when approaching tne atmosphere, in the following way. In term of ψ_1 denote an angle between $\vec{Q}_0$ and the velocity vector and in term of ψ_2 - precession cone semi-angle, and in term of ψ_3 - angle defining the position of the body axis on the surface of the cone (see Fig.4). With Q_0 known, these angles simply define the motion of the vehicle when approaching the atmosphere.

Note that if in terms of Qx_0 and Q_{y_0} we denote projection $\vec{Q}_0$ on the vehicle axis and on the perpendicular to it, it is clear that

$$tg\,\psi_2 = \frac{Q_{y_0}}{Q_{x_0}},$$

i.e. the value of angle ψ_2 determines the value of the vehicle rotation velocity relative to the roll axis.

By using the known values of Q_0, ψ_1 and ψ_2 it is not difficult to find the constants in Equations (1.11). Then using relationships (1.11) for the upper phase of the path and then matching them with Expressions (1.12) at the moment when α becomes sufficiently small, the expression for the angle of attack of the vehicle in lower layers of the atmosphere is found to be (see [6]):

$$\alpha = \frac{e^{-\frac{1}{2}\int_{\tau_i}^{\tau} f_2 d\tau}}{\sqrt{\sqrt{g(\tau)}}} \sqrt{\frac{Q_0}{J_z}} \sqrt{\left(a + b\sin^2\left(\int \sqrt{g(\tau)}\,dt\right)\right)}, \qquad (1.15)$$

where a and b depend on ψ_1 and ψ_2 and are determined by the following expressions

$$\alpha+\beta=\begin{cases}2\left(\sin\frac{\psi_1}{2}+\sin\frac{\psi_2}{2}\right)^2 & at \quad \psi_1+\psi_2<\pi\\ 2\left(\cos\frac{\psi_1}{2}+\cos\frac{\psi_2}{2}\right)^2 & at \quad \psi_1+\psi_2>\pi\,.\end{cases} \qquad (1.16)$$

$$\alpha=\begin{cases}2\left(\sin\frac{\psi_1}{2}-\sin\frac{\psi_2}{2}\right)^2 & at \quad \psi_1+\psi_2<\pi\\ 2\left(\cos\frac{\psi_1}{2}-\cos\frac{\psi_2}{2}\right)^2 & at \quad \psi_1+\psi_2<\pi\,.\end{cases}$$

Considering that $Q_o=\frac{Q_{9o}}{\sin\psi_2}$ find that at a preset equatorial disturbance the amplitude of oscillations α_{max} is proportional

$$\sqrt{\frac{\alpha+\beta}{\sin\psi_2}}=\begin{cases}\sqrt{2}\,\frac{\sin\frac{\psi_1}{2}+\sin\frac{\psi_2}{2}}{\sqrt{\sin\psi_2}} & at \quad \psi_1+\psi_2<\pi\\ \sqrt{2}\,\frac{\cos\frac{\psi_1}{2}+\cos\frac{\psi_2}{2}}{\sqrt{\sin\psi_2}} & at \quad \psi_1+\psi_2>\pi\,.\end{cases} \qquad (1.17)$$

(see Fig.5).

It is apparent that at a fixed angular velocity of rotation about the roll axis (ψ_2) the amplitude value becomes maximum at $\psi=\pi-\psi_2$ and minimum at $\psi_1=0$.

Note that Expressions (1.15-1.17) are valid for all possible relationships of $M(\tau,\alpha)$ satisfying the conditions $M(\tau,\alpha)>0$ at $0<\alpha<\pi$ and $\left.\frac{\partial M}{\partial\alpha}\right|_{\alpha=0}=g(\tau)>0$.

To supplement the study for small values of Ω_o, consider

b) a case of small values of angles ψ_1 and ψ_2 when the equations of motion of the axisymmetrical body are linearized.

As it has already been mentioned above, the conditions of applicability of the asymptotic method at small Ω are violated at some sufficiently narrow transition phase which is at a comparatively high altitude. Along this path phase the value and direction of velocity slightly differ from their values for the re-entry case, and the damping is negligibly small. Regarding this, the linearized equation of the body motion along the transition phase is written in the form

$$\frac{d^2\bar{\delta}}{dt^2}-i\imath\frac{d\bar{\delta}}{dt}+g\bar{\delta}=0. \qquad (1.18)$$

Here $\bar{\delta} = \delta_1 + i\delta_2$, δ_1 and δ_2 - de- Sparr type angles (Fig.6).

In similar conditions the motion along the transition phase has been described in Reference (13).

Introducing new variable $\bar{\alpha} = \bar{\delta} e^{-i\frac{\tau}{2}(t-t_0)}$ we obtain

$$\frac{d^2\bar{\alpha}}{dt^2} + [g(t) + \frac{\tau^2}{4}]\bar{\alpha} = 0. \qquad (1.19)$$

Approximate the density - altitude relation for the "transition phase" by using formula $\rho = \rho_0 e^{-\lambda H}$ and introduce new argument

$$x = \sqrt{\frac{2|m_z^\alpha|\rho S l}{J\lambda^2|\sin\theta|^2}} = \frac{2\sqrt{g}}{\lambda V|\sin\theta|}.$$

Then considering the approximations given above reduce Equation (1.19) to the following form:

$$\bar{\alpha}'' + \frac{\bar{\alpha}'}{x} + (1 + \frac{\mu^2}{x^2})\bar{\alpha} = 0, \qquad (1.20)$$

where

$$\mu = \frac{\tau}{\lambda V|\sin\theta|} = \frac{Q_{x_0}}{J_z\lambda V|\sin\theta|}$$

Parameter μ has the order of the specific time ratio (i.e. $1/\varepsilon$) for the path phase adjacent to the atmosphere boundary.

The solution of Equation (1.20) is:

$$\bar{\alpha} = A J_{i\mu}(x) + B J_{i\mu}(x), \qquad (1.21)$$

where $J_{i\mu}(x)$ - the Bessel function of an imaginary order.

At small x

$$J_{i\mu}(x) = (\frac{x}{2})^{i\mu}\frac{1}{\Gamma(1+i\mu)} + O(x^{2+i\mu}), \qquad (1.22)$$

at large x

$$J_{i\mu}(x) = \sqrt{\frac{2}{\pi x}}\cos(x - \frac{1}{2}\pi i\mu - \frac{\pi}{4}) + O(\frac{1}{x\sqrt{x}}). \qquad (1.23)$$

Using Formula (1.22) determine the values of A and B in term of the initial conditions and then by means of Formula (1.23) predict the amplitude of the oscillations of the body by the angle of attack at the end of the transition phase, where the asymptotic method is applicable. The value of the angle of attack in Resal's axes is equal to $|\bar{\delta}|$ but $|\bar{\delta}| = |\bar{\alpha}|$ therefore, determine the amplitude values of α_{max} and α_{min} (the angle of attack measured in the Resal axes is not set to zero in the general case, but alternately attains maximum and minimum values):

$$\alpha^2_{max} = K_1 + \sqrt{K_1^2 - K_2^2}, \qquad (1.24)$$

$$\alpha^2_{min} = K_1 - \sqrt{K_1^2 - K_2^2}, \qquad (1.25)$$

where

$$K_1 = \frac{\mu}{x\, sh\, \pi\mu}\left[(\psi_1+\psi_2)^2\left(ch^2\frac{\pi\mu}{2} - sin^2\psi\right) + (\psi_1-\psi_2)^2\left(sh^2\frac{\pi\mu}{2} + sin^2\psi\right)\right], \qquad (1.26)$$

$$K_2 = \frac{\mu}{x\, ch\, \pi\mu}(\psi_1^2 - \psi_2^2)\, sh\, \pi\mu, \qquad (1.27)$$

$$\psi = \frac{\psi_3}{2} - \mu \ln\frac{x_0}{2} + arg\, \Gamma(1+i\mu). \qquad (1.28)$$

Consider the structure of angle ψ . At fixed x_0 (fixed initial moment) it comprises a random value of "phase" ψ_3 in this case, it is normal to consider that the values of ψ_3 are equally probable in the range from 0 to 2π, therefore, the values of ψ are also equally probable.

In the case when the value of μ is large, $ch^2\frac{\pi\mu}{2}$ and $sh^2\frac{\pi\mu}{2} \gg 1 \geq sin^2\psi$.

Then the amplitude becomes independent of the initial value of the phase and the results obtained above become valid. The principal feature of the motion at small μ is its dependence on phase ψ_3.

This phenomenon can be interpreted on the following physical basis.

At small values of μ the dynamic pressure buildup along "the intermediate phase" occurs very abruptly and the initial disturbance beyond the atmosphere does not simply define the character of the disturbance motion in the lower layers of the atmosphere, since, in this case, much depends on the phase or angle of attack of the body at the moment when dynamic pressure increases abruptly.

While at large values of μ the specific time of dynamic pressure buildup essentially exceeds the period of the disturbance motion and the initial phase becomes inessential.

Extremes of Expressions (1.24) and (1.25) with respect to ψ are obtained at $\psi = 0$ and $\psi = \frac{\pi}{2}$

$$(\alpha_{max})^2_{max} = \frac{2\mu}{x\, sh\, \pi\mu}(\psi_1 + \psi_2)^2 ch^2 \frac{\pi\mu}{2} \quad (\psi = 0) \qquad (1.29)$$

$$(\alpha_{max})^2_{min} = \frac{2\mu}{x\, sh\, \pi\mu}\begin{Bmatrix}(\psi_1+\psi_2)^2 sh^2 \frac{\pi\mu}{2}\\ (\psi_1-\psi_2)^2 ch^2 \frac{\pi\mu}{2}\end{Bmatrix}\begin{matrix} max\\ (\psi = \pi/2)\end{matrix}$$

$$(\alpha_{min})^2_{min} = \frac{2\mu}{x\, sh\, \pi\mu}(\psi_1 - \psi_2)^2 ch^2 \frac{\pi\mu}{2} \quad (\psi = 0)$$

$$(\alpha_{min})^2_{max} = \frac{2\mu}{x\, sh\, \pi\mu}\begin{Bmatrix}(\psi_1+\psi_2)^2 sh^2 \frac{\pi\mu}{2}\\ (\psi_1-\psi_2)^2 ch^2 \frac{\pi\mu}{2}\end{Bmatrix}\begin{matrix} min.\\ (\psi = \pi/2)\end{matrix}.$$

Asymptotic Equation (1.15), in this case, gives the following result:

$$\alpha^2_{max\,ac} = \frac{\mu}{x}(\psi_1 + \psi_2)^2, \qquad (1.30)$$

$$\alpha^2_{min\,ac} = \frac{\mu}{x}(\psi_1 - \psi_2)^2,$$

hence it follows that

$$\frac{(\alpha_{max})_{max}}{\alpha_{max\,ac}} = \frac{\alpha_{max\,ac}}{(\alpha_{max})_{min}} \doteq \sqrt{cth\,\frac{\pi\mu}{2}}. \qquad (1.31)$$

From consideration of Fig.7 it becomes clear that at $\mu > 1.5$ the difference between the true value of the amplitude and the asymptotic one does not exceed 1%.

Since along the path phase following the transition phase the asymptotic method is applicable, we may neglect the approximations indicated above and write down all the formulas for the amplitude of the angle of of attack, with damping, velocity change and path angle taken into account. To do this, it is sufficient to substitute

$$\left[\frac{e^{-\frac{1}{2}\int f_x dt}}{\sqrt{\sqrt{q}}}\cdot\sqrt{\frac{Q_o}{J_z}}\right]^2$$

for $\frac{\mu}{x}$ in Formulas (1.26), (1.27) and (1.29). The analysis of the written out formulas permits getting an idea of the character of the motion at various values of μ. Thus, for example, it turns out that at small μ the motion of the body in the lower layers of the atmosphere almost in all the cases becomes "near to planar" in the sense that the ratio $\frac{\alpha_{min}}{\alpha_{max}}$ becomes small.

The obtained results for the general case of the motion at small ψ_1 and ψ_2 have not been analysed in Reference [13].

2. Consider the motion of the vehicle with a high positive lift-drag ratio (so called "skip motion" [14]) as a second example of usage of the asymptotic method.

After introducing some generally-accepted approximations ($|\theta| \ll 1$, $\rho = \rho_0 e^{-\lambda H}$, C_x = const.) the equation of motion is reduced to the Form [15], [9]:

$$\frac{d^2 y}{dx^2} = -\sqrt{R\lambda}\,\frac{C_y}{C_x} + \frac{e^{2x} - 1}{y} \tag{2.1}$$

where

$$x = \ln \frac{\sqrt{Rg}}{V}, \quad y = \frac{C_x S}{2m}\sqrt{\frac{R}{\lambda}}\,\rho .$$

Without giving detailed transformations (see [9]) write a final formula which gives the amplitude values of altitude versus velocity

$$\frac{C_y}{\left(\frac{Rg}{V^2} - 1\right)^{3/2}}\, h\left[\frac{C_y S R \rho_{max}}{2m\left(\frac{Rg}{V^2} - 1\right)}\right] = const \tag{2.2}$$

Here the argument of function h is a ratio of maximum "amplitude density" ρ_{max} to the density corresponding to the quasy-steady glide path [14]

$$\rho_* = \frac{2m\left(g - \frac{V^2}{R}\right)}{C_y S V^2}$$

Function h (u) is predicted by the formula:

$$h(u) = \int_{z_1(u)}^{z_2(u)} \sqrt{u - z + \ln z/u}\; dz \tag{2.3}$$

where Z_1 (u) and Z_2 (u) = u the roots of equation

$$u - z + \ln z/u = 0.$$

The plotted function h (u) is given in Fig.8.

At $u \approx 1$

$$h(u) \approx \frac{\pi}{2\sqrt{2}}(u-1)^2 \tag{2.4}$$

at $u \gg 1$

$$h(u) \approx \frac{2u\sqrt{u}}{3} \tag{2.5}$$

Substituting approximate formulas (2.4) or (2.5) into relationship (2.2) we get results corresponding to the results given in Reference 16 or 14 , respectively.

Formula (2.2) combines the two extreme cases considered in these papers.

3. In conclusion dwell on the problem of accomplishing a more rapid numerical integration when studying the motion approaching the Keplerian one.

The asymptotic methods are highly effective when solving this problem.

If we introduce osculating variables a and b by means of formula

$$y = \frac{1}{r} = \frac{1 + a\cos\vartheta + b\sin\vartheta}{p}; \quad \frac{dy}{d\vartheta} = \frac{-a\sin\vartheta + b\cos\vartheta}{p} \tag{3.1}$$

where r - radius vector, ϑ - polar angle, and p - ellipse parameter, then the equations for the planar case are reduced, as it is known, to the form (see e.g. [7]).

$$\frac{da}{d\vartheta} = \frac{1}{\mu y^2}\left[j_r \sin\vartheta + j_\tau\left(-\frac{1}{y}\frac{dy}{d\vartheta}\sin\vartheta + 2\cos\vartheta\right)\right], \tag{3.2}$$

$$\frac{db}{d\vartheta} = \frac{1}{\mu y^2}\left[-j_r\cos\vartheta + j_\tau\left(\frac{1}{y}\frac{dy}{d\vartheta}\cos\vartheta + 2\sin\vartheta\right)\right],$$

$$\frac{dp}{d\vartheta} = \frac{2}{\mu y^3} j_\tau$$

Here $\mu y^2 = g(r)$ where g (r) - acceleration of gravity; j_r and j_τ - projection of disturbance acceleration on the radius vector and transversal.

When studying the motion approaching the Keplerian one when disturbance acceleration is small, Equations (3.2) can be re-written in the following standard form:

$$\frac{dx_i}{d\vartheta} = \varepsilon X_i (x_1 \ldots x_n, \vartheta), \tag{3.3}$$

where $\varepsilon \approx \frac{|j|}{g}$ - low parameter.

It is important to note that in cases when j_z and j_τ do not evidently depend on polar angle ϑ, functions X_i have with respect to ϑ a period equal to 2π.

Further, this condition will be supposed feasible. In conformity with the said in paragraph 1 the principal terms of the asymptotic solution of the set of Equations (3.3) are determined from the average set of Equations

$$\frac{dx_i}{d\vartheta} = \varepsilon \frac{1}{2\pi} \int_0^{2\pi} X_i (x_1 \ldots x_n, \vartheta)\, d\vartheta \tag{3.4}$$

Here, when calculating the integrals, variables $x_1 \ldots x_n$ are considered parameters. These equations describe a circular drift of the osculating elements during a great number of revolutions of a vehicle relative to the centre of attraction.

If the integrals incorporated in the right-hand parts of Equations (3.4) can be calculated analytically, then subsequent numerical integration of these equations is a rather simple problem, as the solution of the set of Equations (3.4) does not contain rapidly changing components. In this case, the averaging of the equations allows reducting machine time, required for calculations, $1/\varepsilon$ times. However, with a rather complex relation between acceleration components j_z and j_τ and the parameters of motion, these integrals have to be calculated numerically (see, for example [11]). In this case, it is necessary to do it in each step of numerical integration of Equations (3.4) in the course of calculating their right-hand parts. Due to this, in the last case the averaging of the equations is advisable only when the condition of applicability of the asymptotic method is feasible with a rather great margin. But for these cases a method of a more rapid numerical integration of the equations in the osculating variables may be suggested, which does not require calculation of the integrals in the right-hand parts of the average equations and, owing to this, substantially simplfies programming (see [10] , [7]).

Introduce into the consideration one more fictitious set of equations, differing from Equations (3.3) only in having in its right-hand parts a larger period T than 2π with respect to ϑ:

$$\frac{dx_i}{d\vartheta} = \varepsilon X_i\left(x_1, \ldots, x_n, \frac{2\pi}{T}\vartheta\right) \quad (i=1,\ldots,n) \qquad (3.5)$$

When averaging this set of equations, average the right-hand parts with respect to T. Note the following equation

$$\frac{1}{2\pi}\int_0^{2\pi} X_i\,(x_1, \ldots, x_n, \vartheta)\,d\vartheta = \frac{1}{T}\int_0^{T} X_i\left(x_1,\ldots,x_n,\frac{2\pi}{T}\vartheta\right)d\vartheta \qquad (3.6)$$

where $x_1, \ldots, x_n$ and T are considered parameters. This equation is prove by a simple replacement of the integration variable. It apparently follows from Equation (3.6) that the average sets of equations for sets of (3.3) and (3.5), respectively, coincide. This means that the average characteristics of the solutions of Equations (3.3) and (3.5) should also coincide (see Fig.9). Thus, the average characteristics of the solutions of the initial set of Equations (3.3) can be obtained by numerical integration of the set of Equations (3.5). If we consider that the numerical integration step required is at least proportional to the period of the right-hand parts of the equations with respect to ϑ (see [10]), then it follows that we can gain time, required for numerical integration, $T/2\pi$ times when integrating the set of Equations (3.5) instead of the set of Equations (3.3). Ratio $T/2\pi$ is limited from above by the condition of applicability of the asymptotic method to Equations (3.5) with an increased period of the right-hand parts. The main condition of applicability of this method consists in the fact that change in X_1 in each interval of change in ϑ with the length of order T would be small as compared with ΔX_1 - complete change in X_1 within the entire considered interval of change in ϑ.

Using this condition it is not difficult to obtain the following approximate formula for selecting period T

$$\frac{T}{2\pi} \approx \varepsilon_{max}\frac{g(\tau)}{j} \qquad (3.7)$$

where $j = |\vec{j}|$ and ε_{max} - maximum permissible error.

This formula also permits evaluating the gain in time which is got when integrating the set of Equations (3.5) instead of integrating the set of Equations (3.3).

Thus, for example, at $\mathcal{E}_{max} = 0.1$ and $\dot{f}/g(z) = 0.01$ machine time required for the calculations can be decreased 10 times. The method described above may be called a method of artificial increase in period.

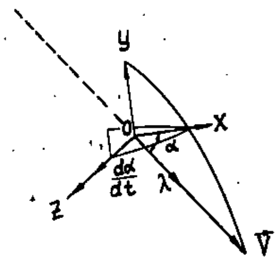

Fig. 1

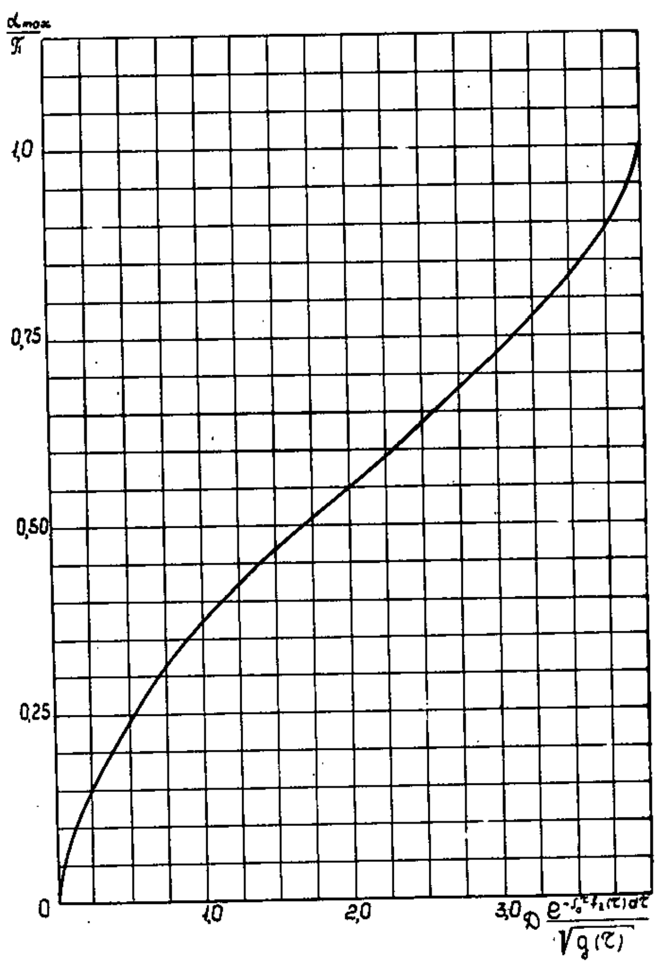

Fig. 2

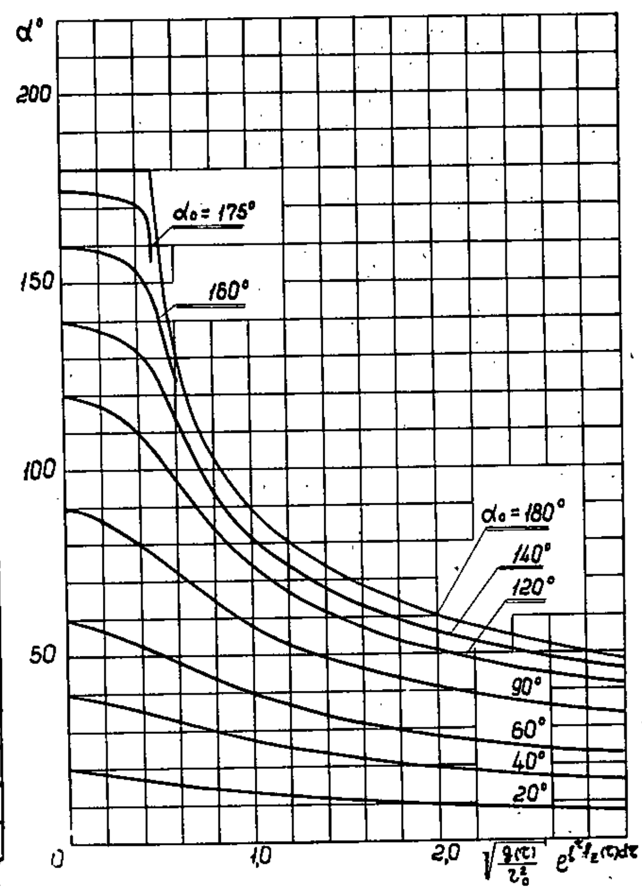

Fig. 3

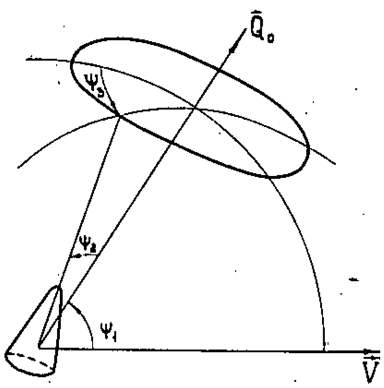

FIG. 4

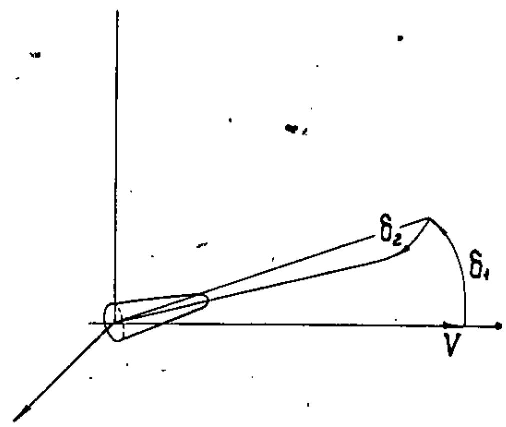

FIG. 6

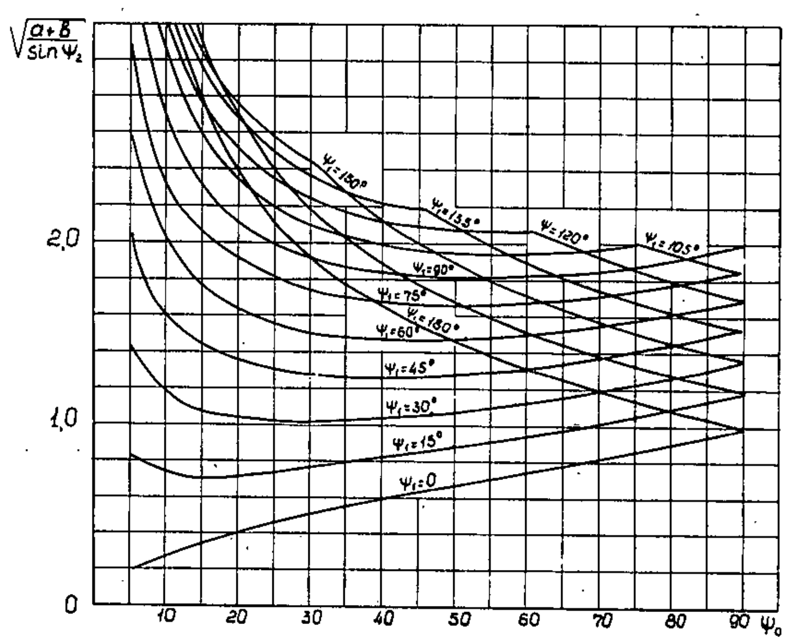

FIG. 5

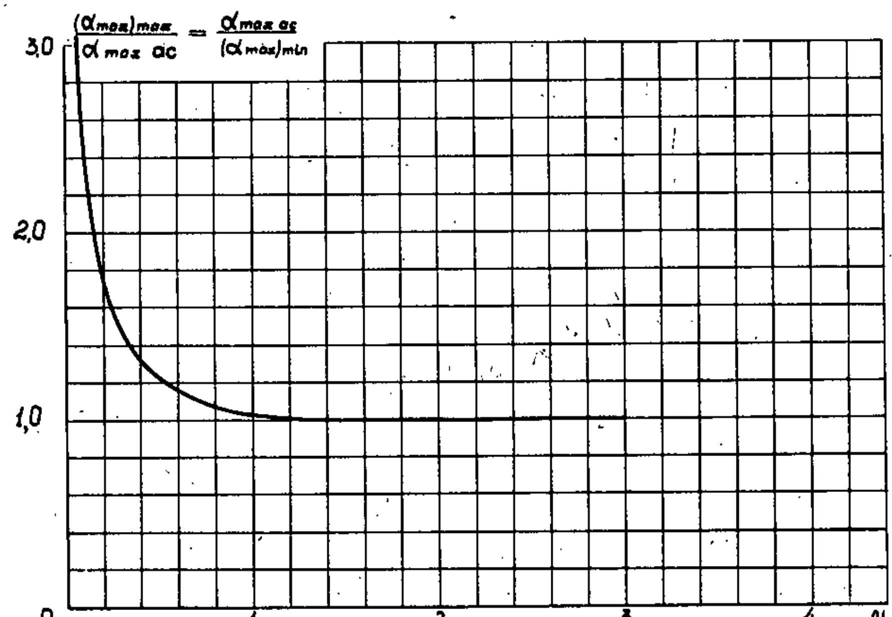

FIG. 7

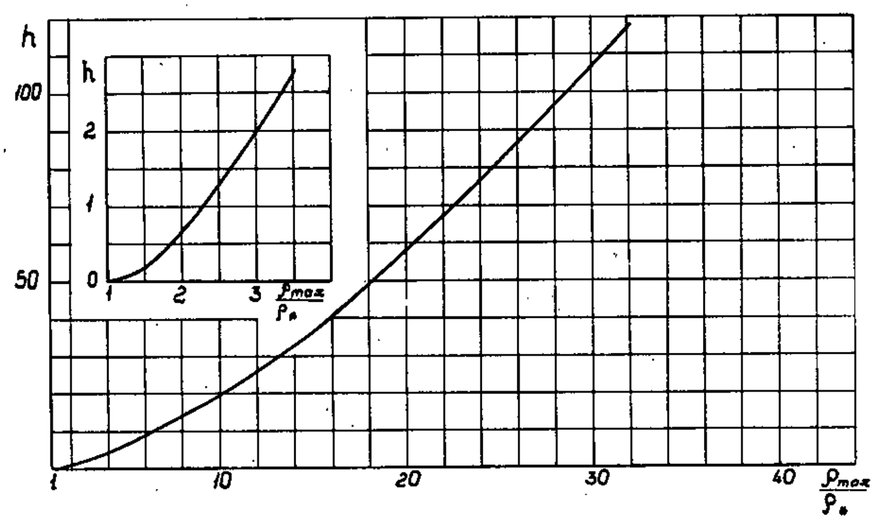

FIG. 8

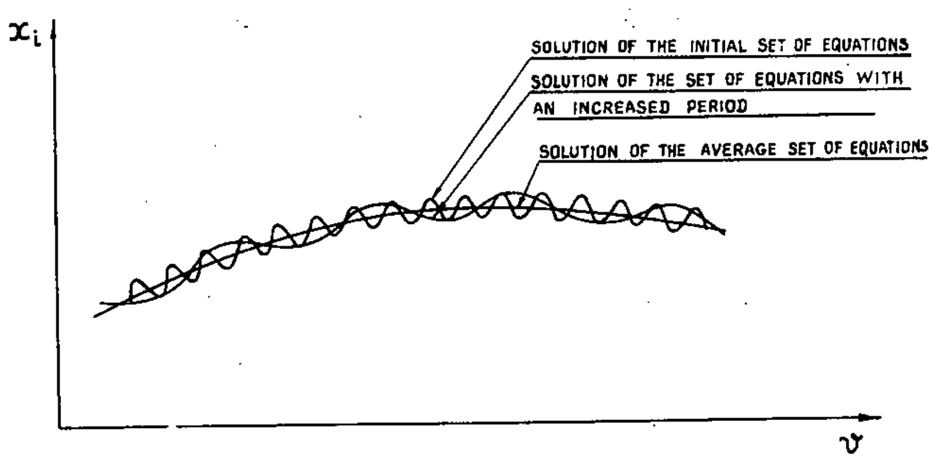

FIG. 9

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А.Л. Стасенко

О ФОРМЕ ТЕПЛООТВОДЯЩИХ ЭЛЕМЕНТОВ, ОХЛАЖДАЕМЫХ ИЗЛУЧЕНИЕМ. ЧАСТЬ III. ФОРМА ГИБКОЙ НИТИ В ПОЛЕ ЦЕНТРОБЕЖНЫХ СИЛ.

Аннотация

Предыдущие I и II части работы были посвящены определению оптимальных форм теплоотводящих ребер, охлаждаемых излучением.[x/] В настоящей III части рассмотрена форма свободной ленты /гибкой нити/, которая обкатывает охлаждаемый цилиндр и излучает со своей поверхности отнятое от цилиндра тепло.

Показано, что форма гибкой нити под действием центробежных и кориолисовых сил, возникающих при вращении нити с постоянной угловой скоростью ω, описывается суммой эллиптических интегралов первого и третьего рода. Определены натяжение нити и длина участка касания ее с цилиндром.

Найдено, что нити одинаковой относительной длины подобны, т.е. их форма не зависит от угловой скорости, если линейная скорость пропорциональна ω. Указаны способы улучшения условий теплопередачи от цилиндра к ленте путем увеличения длины участка соприкосновения ленты с цилиндром и натяжения ленты.

x/ См., Гродзовский Г.Л. доклад на XII конгрессе МАФ и Г.Л. Гродзовский, В.В. Фролов доклад на XIII конгрессе МАФ.

G.L. Grodzovsky
A.L. Stassènko

SUR LA FORME DES ELEMENTS D'EMISSION. PARTIE III. LA FORME DU FIL FLEXIBLE DANS LE CHAMP DES FORCES CENTRIFUGES.

Annotation.

Les parties précédentes I et II du travail sont consacrées à la définition des formes optima des ailettes d'émission.x)

Dans cette partie on envisage la forme de la bande libre (fil flexible) qui enveloppe le cylindre refroidi et emit de la surface la chaleur pris du cylindre.

La forme du fil flexible est decrit par la somme des intégrales elliptiques du première et deuxième genres sous l'action de la force centrifuge et la force centrifuge composée qui surgissent au temps de rotation du fil avec la vitesse angulaire ω constante, On a étable la tension du fil et la longueur de la section contractée avec le cylindre. On a trouvé que les fils de la longueur pareil relative sont semblables, c'est à dire leur forme ne dépend pas de la vitesse angulaire, si la vitesse linéaire est proportionelle à ω. On a montré les moyens à améliorer les conditions de refroidissement de cylindre à la bande à l'aide d'augmentation de la longueur de la section contractée à la bande avec le cylindre et de la tension de la bande.

x) Le rapport fait à XII congres d'IAF par m-r Grodzovsky et le rapport fait à XIII congres d'IAF par m-rs Grodzovsky et Frolov.

G.L. Grodsowsky
A.L. Stassenko

ÜBER DIE FORM DER WÄRMELEITENDEN ELEMENTE MIT STRAHLUNGSKÜHLUNG. 3. TEIL.
DIE FORM DES BIEGSAMEN FADENS IM ZENTRIFUGALKRAFTFELD.

Übersicht.

Zwei erste vorhergehende Teile der Arbeit waren der Bestimmung der Optimalform der wärmeableitenden Rippen (mit Strahlungskühlung) gewidmet.[x)]

Im vorliegenden dritten Teil ist die Form des freien Bandes (des biegsamen Fadens) betrachtet, das den zu kühlenden Zylinder umfasst und die vom ihm abgenommene Wärme von seiner Oberfläche ausstrahlt.

Es ist gezeigt, das die Form des biegsamen Fadens unter dem Einfluss der bei der Fadenrotation mit konstanter Winkelgeschwindigkeit ω auftretenden Zentrifugal - und Coriolis-Kräfte durch die Summe der elliptischen Integralen der ersten und dritten Art beschrieben wird. Es sind die, Fadenspannung und Berührungsstrecke des Fadens mit dem Zylinder bestimmt. Es ist festgestellt, das die Fäden mit gleichen Relativlängen ähnlich sind, d.h, ihre Form von der Winkelgeschwindigkeit unabhängig ist, wenn die Lineargeschwindigkeit ω proportional ist. Es sind die Verfahren zur Verbesserung der Wärmeübergangsverhältnisse vom Zylinder zum Band mittels Verlängerung der Zylinder-Band-Berührungsstreske des Bandes und Vergrösserung, der Bandspannung gezeigt.

x) Siehe G.L. Grodsowsky, Vortrag, gehalten auf dem 12. Kongress IAF und G.L. Grodsowsky, W.W. Frolov, Vortrag, gehalten auf dem 13. Kongress IAF.

Summary

In the two previous parts of the paper radiating fins of optimum contour were discussed.x)

In this part the form of a free belt (flexible thread), rolling around the cylinder to be cooled, and radiating the heat removed from the cylinder into space is considered.

The form the thread takes under the influence of centrifugal and Coriolis forces induced by its rotation with a constant angular speed ω is shown to be expressed in terms of the sum of elliptic integrals of the first and third kind.

Tension of the thread and the contact line length are derived. The threads of equal dimensionless length are found to be similar, i.e. their form does not depend upon angular speed, if the linear velocity is proportional to ω. Some means are indicated to increase heat transfer from the cylinder to the belt by increasing the contact line length and tension.

In the paper [1] the scheme of the belt radiator (Fig.1) was discussed in which a flexible belt pressed by rollers to the cylinder removes the heat from the cylinder and radiates it from its surface. It is of interest to examine a free belt pressed to the cylinder by centrifugal forces induced by the rolling of the belt around the cylinder with a certain angular speed. The problem of determining the form of the belt, its tension and its area of contact with the cylinder is reduced to the problem of a flexible thread in the centrifugal force field which is the topic of this paper.

It is assumed that a flexible thread having length L and density per unit of length μ rotates with a certain constant speed $\overline{\omega}$ around a cylinder with radius r_0 and moves simultaneously with a modulus-constant speed $\overline{V}$ (Fig.2).

If the thread rolls around the fixed cylinder without sliding, $V = r_0\omega$. Within the limits of the angle $2\varphi_0$ a part of the thread contacts the cylinder.

The form of the thread $r(\varphi)$, its length of contact with the cylinder and its tension are to be determined.

The force of inertia acting upon the thread element ds is

$$d\overline{F} = \left[\mu\omega^2\overline{r} - (2\mu V\omega - \mu\varkappa V^2)\overline{n}_0\right]ds = \overline{\Phi}ds \qquad /1/$$

x) G.L. Grodzovsky, Report at the XII IAF Congress.
G.L. Grodzovsky and V.V. Frolov, Report at the XIII IAF Congress.

where $\varkappa$ is the curvature of the thread,
$\bar{n}_0$ is the orth of the normal to it,
$\bar{\Phi}$ is the force per unit of length and
$\bar{r}$ is a radius-vector.

It can be shown that the balanced form of the free flexible thread is described by the equation

$$\bar{\Phi} + \frac{d}{ds}\left(\lambda \bar{\tau}_0\right) = 0 \qquad /2/$$

where λ is the tension of the thread,
$\bar{\tau}_0$ is the orth of the tangent.

In the proposed problem the form of the thread will be a flat curve perpendicular to $\bar{\omega}$.

Writing Equations /1/ and /2/ in projections on the axes $\bar{\tau}_0$ and $\bar{n}_0$ we derive correspondingly

$$\frac{d\Lambda}{d\sigma} + \frac{\rho'^2}{(\rho^2+\rho'^2)^{1/2}} = 0 \qquad /3/$$

$$\pm\frac{2\rho^2}{(\rho^2+\rho'^2)^{1/2}} + 2b - \Lambda K + \frac{b^2}{2}K = 0 \qquad /4/$$

Here

$$\rho = \frac{r}{r_0}, \quad b = \frac{2V}{\omega r_0}, \quad \sigma = \frac{s}{r_0}$$

$$\Lambda = \frac{\lambda}{1/2\,\mu\omega^2 r_0^2}, \quad a = \frac{\lambda_0 - \mu V^2}{1/2\,\mu\omega^2 r_0^2}, \quad K = \frac{\rho^2+2\rho'^2-\rho\rho''}{(\rho^2+\rho'^2)^{1/2}} \qquad /5/$$

The double sign in Equation /4/ takes into account the fact that $\rho(\varphi)$ may not be a simple function, the positive sign being chosen for $\varphi < \varphi_*$ and the negative sign for $\varphi > \varphi_*$, where ρ_*, φ_* is a point dividing simple branches of the curve $\rho(\varphi)$ (at this point $\frac{d\rho}{d\varphi} = \infty$).

The initial conditions have the following form $\rho = 1, \ \rho' = 0$ with $\varphi = \varphi_0$. /6/

After integrating /3/ we get

$$\Lambda - \frac{b^2}{2} = a + 1 - \rho^2 \qquad /7/$$

The substitution of the variables

$$\rho^2 = \xi, \qquad \frac{\rho^2}{(\rho^2+\rho'^2)^{1/2}} = \eta \qquad /8/$$

reduces the curvature K and Equation /4/ to the form $K = 2\frac{d\eta}{d\xi}$

$$\pm\eta + b - (a+1-\rho^2)\frac{d\eta}{d\xi} = 0$$

hence

$$\eta^{(1)} + b = \frac{C_1}{a+1-\xi}, \qquad K^{(1)} = \frac{2C_1}{(a+1-\xi)^2} \quad (\xi \leq \xi_*)$$

$$-\eta^{(2)} + b = C_2(a+1-\xi), \quad K^{(2)} = 2C_2 \qquad (\xi \geq \xi_*) \qquad /9/$$

Thus the thread may consist of pieces of two kinds: with variable curvature $K^{(1)}$ and arcs of circumferences with curvature $K^{(2)}$ = const. From the conditions of their contact of the first kind when $\xi = \xi^* = 1 - \frac{a}{b}$, $\eta^{(1)} = \eta^{(2)} = 0$ we have $C_1 = a(1+b)$, $C_2 = \frac{b^2}{a(1+b)}$

and $K^{(1)}(\xi_*) = K^{(2)}(\xi_*)$, i.e. the contact of the second kind, which is quite natural. It is evident that the curvature of the thread has a fixed sign and its absolute magnitude does not decrease with ξ. It is negative with $b > -1$ and the thread has a point of self-intersection. Therefore the flexible thread is a mathematical model of the flexible belt when $b > -1$, Considering the former variables and integrating Equation /9/, we get [2]

$$\varphi - \varphi_0 = \int_1^{\rho} \frac{[a + b(\rho^2-1)]\, d\rho}{\rho^2 \sqrt{[a-(\rho^2-1)]^2 - [a+b(\rho^2-1)]^2/\rho^2}} \qquad /10/$$

The equality $\rho' = 0$ is fulfilled at the points where the radicand turns into zero:

$$\rho^2[a-(\rho^2-1)]^2 - [a+b(\rho^2-1)]^2 = 0$$

This equation, cubic relative to ρ^2, has three valid roots.

$$\rho_1^2 = 1, \quad \rho_{2,3}^2 = a + \frac{b^2+1}{2} \mp \frac{1}{2}\sqrt{4a(b+1)^2 + (b^2-1)^2}$$

In the interval $\rho_2 < \rho < \rho_3$ the radicand is negative but, since ρ is continuous, only two roots out of three have a physical meaning: the first indicates that the thread contacts the drum (see the initial terms /6/) the second defines the greatest radius $\rho_2 = R$, so that

$$1 \leq \rho \leq R, \quad \varphi_0 \leq |\varphi| \leq \pi$$

Integral /10/ which defines the form of the thread is divided into two elliptic integrals of the first and third kind, which by substitution

$$\rho^2 - 1 = (\rho_2^2 - 1)\sin^2\psi \qquad /11/$$

are reduced to the canonical form of Legendre

$$\varphi - \varphi_0 = \frac{b}{\sqrt{\rho_3^2-1}} \int_0^{\psi} \frac{d\psi}{\sqrt{1-k^2\sin^2\psi}} + \frac{a-b}{\sqrt{\rho_3^2-1}} \int_0^{\psi} \frac{d\psi}{(1+h^2\sin^2\psi)\sqrt{1-k^2\sin^2\psi}} = \qquad /12/$$

$$= \frac{b}{\sqrt{\rho_3^2-1}} F(\psi, k) + \frac{a-b}{\sqrt{\rho_3^2-1}} \Pi(\psi, h, k)$$

The angle φ_0 is defined by $\varphi = \pi$ with $\rho = R$ ($\psi = \frac{\pi}{2}$)

$$\pi - \varphi_0 = \frac{b}{\sqrt{\rho_3^2-1}} K_1(k) + \frac{a-b}{\sqrt{\rho_3^2-1}} \Pi(h, k) \qquad /13/$$

where $K_1(k)$ and $\Pi(h,k)$ are full elliptic integrals.

In Equations /12/ and /13/

$$h^2 = \rho_2^2 - 1, \quad k^2 = \frac{\rho_2^2-1}{\rho_3^2-1}$$

So, the functions $\rho = \rho(\varphi, a, b)$ and $\varphi_0(a, b)$ are found.

The correlation

$$\frac{1}{r_0}\int_0^L ds = \ell \qquad /14/$$

connects the obtained values with the relative length of the thread $\ell = \frac{L}{r_0}$

The case V = b = 0 allows an analog with the motion of a material particle. In this case the force Φ /2/ is central and has a potential function U(r): $\Phi(r) = \text{grad}\, U(r)$, $U(r) = \frac{\mu\omega^2}{2} r^2$.

Then, as is known, the form of the thread is identical with the trajectory of a free material particle with the mass m moving in a central field with the force function

$$U_1(r) = \frac{m}{2}\left[U(r) - \gamma\right]^2,$$

the initial position of the particle coinciding with the beginning of the thread and the initial speed $V_0 = \lambda_0$. In this case the angular momentum is equal by the modulus to $A = r_0\lambda_0$ and is perpendicular to the plane of the thread. The form of the thread is defined by the quadrature

$$\varphi - \varphi_0 = \int_{r_0}^{r} \frac{A\,dr}{r^2\sqrt{(\frac{1}{2}\mu\omega^2 r^2 - \gamma)^2 - A^2/r^2}} \qquad /15/$$

which coincides with Equation /2/ in case b = 0 and is an elliptic integral of the third kind.

If $V = Cr_0\omega$, where C is a constant (e.g. $V = r_0\omega$, the thread rolls around the cylinder without sliding) or V = 0, then $\rho = \rho(\varphi, \ell)$, $\varphi_0 = \varphi_0(\ell)$, i.e. threads of the same relative length are similar and, therefore, the form of the thread is independent of the angular speed.

To improve the conditions of heat transfer from the cylinder to the belt it may be desirable to increase the length of contact between the belt and the cylinder. It is assumed that an auxiliary cylinder with the radius r_1, and mass M_1 moves freely along the thread and is repulsed by the centrifugal forces to the maximum distance from the point 0 (Fig.3) thus stretching the thread and increasing φ_0 and λ_0.

The form of the thread is known, the parts of the thread contacting the cylinder are arcs of circumferences with radii r_0 and r_1, and the form of the thread between the points of contact with the cylinders is described by elliptic integrals /12/. We derive the unknown λ_0 and φ_0 from Relation /14/ and

$$2\lambda_0 \sin\varphi_0 = 2\int_{r_0\varphi_0}^{\frac{L}{2}} \Phi_x\, ds + M_1\omega^2 r_2^2, \qquad /16/$$

where r_2 is a radius-vector of the point of application of resultant of centrifugal forces acting upon the cylinder M_1.

The results of the calculations of the form of the thread made with the help of elliptic integral tables are shown in Fig.4 for V = 0.

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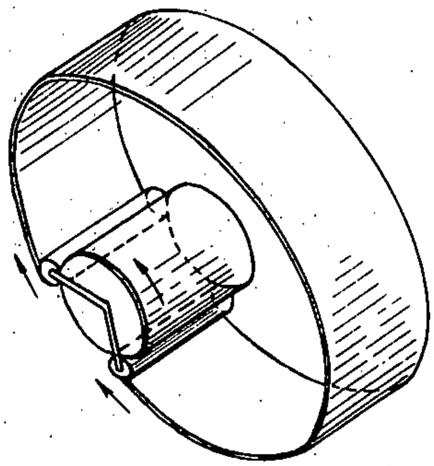
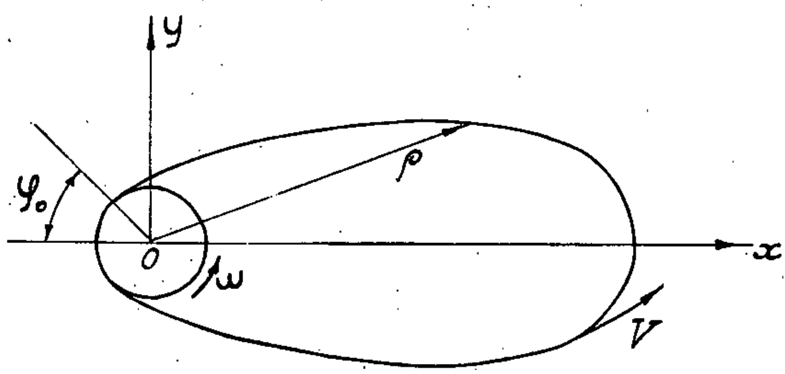
1. Weatherston R.C. and Smith W.E. A Method of Heat Rejection from Space Powerplants. "ARS J." 1960, III, v.30, N 3, p.268-269.

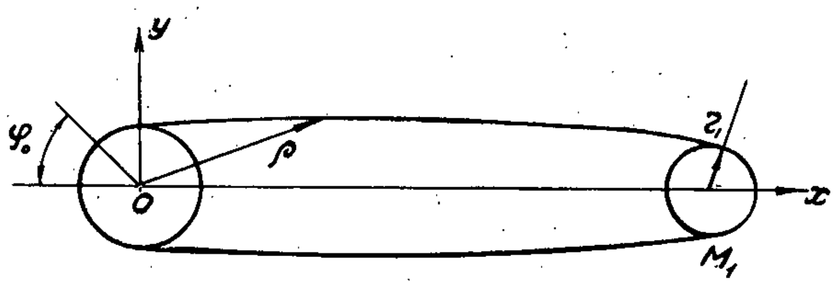
2. Стасенко А.Л. Форма гибкой нити в поле центробежных сил. ... АН СССР, ОТН, № 6, 1962.



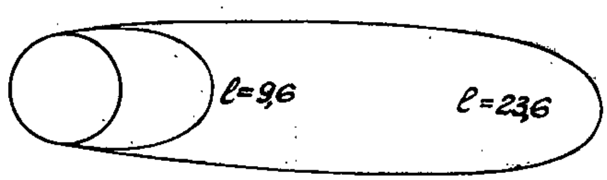
Фиг. 1 [1]



Фиг. 2



Фиг. 3



Фиг. 4

GRODZOVSKY G.L.,IVANOV I.N.,TOKAREV V.V.

ON THE MOTION OF A BODY OF VARIABLE MASS WITH CONSTANT AND DECREASING POWER CONSUMPTION IN A GRAVIATIONAL FIELD

Part III

1963

О ДВИЖЕНИИ ТЕЛА ПЕРЕМЕННОЙ МАССЫ С ПОСТОЯННОЙ И УБЫВАЮЩЕЙ ЗАТРАТОЙ МОЩНОСТИ В ГРАВИТАЦИОННОМ ПОЛЕ.

Часть Ш.[x/]

Гродзовский Г.Л., Иванов Ю.Н., Токарев В.В.

АННОТАЦИЯ

п.9. Рассматривается задача об оптимизации параметров движения тела переменной массы с ограниченной затратой мощности при нелинейной зависимости веса источника мощности от величины мощности. Установлено, что важное свойство - разделение общей вариационной проблемы на две частные: а) определение оптимальной величины мощности или закона уменьшения ее по времени и б) определение оптимального закона изменения вектора ускорения от реактивной тяги вдоль траектории, сохраняется независимо от вида функциональной связи между мощностью и ее весом. Как и при линейной функциональной связи определяющим для второй задачи является интеграл от квадрата ускорения от реактивной тяги по времени. Указан общий критерий выбора оптимальной мощности и приведен пример для случая степенной зависимости между мощностью и ее весом.

п.10. Рассмотрена общая задача о движении тела переменной массы с заданным активным временем. Введение категории заданного активного времени позволяет установить количественные характеристики для движения с ограниченным временем работы источника мощности и с другой стороны, дать некоторые качественные выводы, независящие от вида гравитационного поля. Вес источника мощности предполагается постоянным, ибо оптимальное уменьшение веса мощности незначительно улучшает характеристики (см.п.6).

Получены следующие результаты.

1°. Как и в случае оптимального активного времени при оптимальной программе направления вектора тяги, независимо от характера программирования расхода рабочего тела, мощность должна быть максимально возможной на активных участках траектории.

2°. Включение участков с нулевой тягой в траекторию движения с переменным оптимальным расходом ухудшает характеристики. Количественное ухудшение функционала задачи может быть определено на основании результатов работы для заданной продолжительности пассивного участка.

3°. На траектории с постоянной тягой при задании пассивных участков, отличных от оптимальных, также может быть подсчитано ухудшение характеристик задачи.

4°. Известно, что для случая переменного оптимального расхода (см.п.6) выбор оптимального распределения веса между мощностью и запасом рабочего вещест-

[x/]Часть I и П, п.1-8, см. доклады на ХП и ХШ Конгрессах МАФ.

ва является задачей независимой от траекторных расчетов; при постоянном расходе (постоянной тяге) траекторная и весовая части задачи являются взаимосвязанными.

Для приведенных в работе примеров расчетов оптимизация проведена не только в смысле оптимальной программы направления вектора тяги, но и в смысле оптимального соотношения весов источника мощности и рабочего вещества. Параметром, отвечающим за оптимизацию весов для случая постоянной тяги, является отношение весового расхода к начальному весу.

В качестве функционала проблемы рассматривалась величина относительной полезной нагрузки. Изучались два класса задач динамики: перемещение из одной фиксированной точки фазового пространства в другую и набор заданного модуля скорости.

Получены решения двух задач о движении в бессиловом поле. Проведено сравнение полезных нагрузок в следующих случаях: а) движение с постоянной тягой и оптимальным пассивным участком, в) движение с переменным оптимальным расходом и пассивным участком, совпадающим по продолжительности со случаем постоянной тяги, с) движение с переменным оптимальным расходом без пассивных участков и д) движение с активными временами, составляющими заданные части от полных времен перемещения.

п.II. В свете идей Ф.А.Цандера об использовании ненужных элементов конструкции в качестве рабочего вещества (топлива) рассматривается задача о максимальной полезной нагрузке при активном сбросе ступеней источника мощности с заданным коэффициентом превращения отключаемых ступеней в рабочее вещество. Получены следующие результаты:

1^0. В каждый момент времени мощность реактивной струи (как и в случае постоянного веса источника) и коэффициент использования отбрасываемой части источника мощности в качестве рабочего вещества должен быть максимально возможными.

2^0. Оптимальный закон изменения веса источника мощности состоит из участка постоянного веса, участка пропорционального изменения веса источника и запаса рабочего вещества, и участка, на котором запас рабочего вещества израсходован, а тяга создается только за счет превращения отбрасываемой части источника мощности в рабочее вещество.

3^0. Оптимальный закон ускорения от тяги, как и в п.I,6, должен обеспечивать минимум интеграла от квадрата этого ускорения.

4^0. Активный сброс мощности дает существенный выигрыш в полезной нагрузке.

5^0. К предельным значениям полезной нагрузки, соответствующим непрерывному уменьшению веса источника мощности, можно приблизиться при конечном сравнительно небольшом числе секций источника.

п. I2. Производится построение оптимальной, с учетом коррекции, программы ускорения от реактивной тяги, обеспечивающей максимум осредненной полезной нагрузки при движении тела переменной массы с постоянной затратой мощности. Предполагаются известными корреляционная функция случайных отклонений от программы моторного ускорения и дисперсии ошибок измерений положения и скорости тела. Оптимальные поправки к программе моторного ускорения выбираются из условия минимума интеграла от квадрата ускорения при движении от измеренного положения до заданного конечного положения за оставшийся промежуток времени. После этого задача сводится к выбору такого распределения моментов коррекции (моментов перестройки программы ускорения), и такого их числа, которые обеспечили бы минимум осредненной величины приращения интеграла от квадрата моторного ускорения при условии попадания траектории в заданную область конечных значений.

На примере движения в бессиловом поле для специального вида корреляционной функции отклонений от программы моторного ускорения показано, что:

1^0. В случае точных измерений интервалы между моментами коррекции образуют геометрическую прогрессию, уменьшаясь к концу движения.

2^0. Для точных измерений не существует оптимального числа моментов коррекции - приращение функционала уменьшается с увеличением числа моментов коррекции.

3^0. При наличии зависимости дисперсий ошибок измерений от интервала между моментами коррекций должно существовать оптимальное число моментов коррекции.

ON THE MOTION OF A BODY OF VARIABLE MASS WITH CONSTANT AND DECREASING POWER CONSUMPTION IN A GRAVIATIONAL FIELD. PART III.x)

By Grodzovsky G.L., Ivanov I.N. and Tokarev V.V.

Summary

Section 9. The problem of the motion parameters optimization of a body of variable mass with limited power consumption for the case of non-linear dependence of the power source weight on the power value is considered. As in the case of linear dependence the general variational problem is divided into two particular problems: a) the definition of the optimum power value or the law of its time decrease and b) the formulation of the optimum law of the thrust acceleration vector variation along a trajectory. It is found that this division is kept independent of the kind of functional relations between power and power source weight. As well as in the case of linear functional relation the time integral of the square thrust acceleration is used as a basic parameter for the second problem. A general criterion for optimum power choice is found and an example of power dependence between the power value and the power source weight is given.

Section 10. The general problem of the motion of a variable mass body with prescribed active time (power-on time) is considered. On the one hand, the introduction of the category of the prescribed active time allows determining the quantitative characteristics of motion with limited life time of the power source and, on the other hand, it allows obtaining some qualitative results independent of the kind of a gravitational field. The power source weight is assumed to be constant since optimum decrease in the power source weight improves the characteristics only to a small degree (see Section 6).

The following results were obtained:

1°. As well as in the case of optimum active time for the optimum program of the thrust vector direction, independent of the propellant consumption program, power should be as maximum as possible on the power-on phase of the flight path.

2°. When the flight path with variable optimum propellant consumption includes null-thrust phases, the parameters of motion are deteriorated. The quantitative increase in the functional of the problem for the given power-off phase may be obtained on the basis of the results of this report.

3°. The deterioration of the characteristics may be also calculated along the constant thrust trajectory with given power off phases different from optimum ones.

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x) See Part I and Part II, Sections 1-8 (The reports at the XII-th Congress and at the XIII-th Congress of IAF).

4°. It is known that in the case of a variable optimum propellant consumption (see Section 6) the choice of the optimum weight breakdown between the power source and the propellant storage is independent of the trajectory analysis; with the constant propellant consumption (constant thrust) the trajectory and the weight parts of the problem are interconnected. For the analysis examples given here optimization was used not only for the thrust vector direction optimum program but also for the power source and propellant optimum weight ratios. Weight rate-initial weight ratio is assumed to be an optimization parameter for the case of constant thrust. The relative payload was taken as the functional of the problem. Two problems of dynamics were considered: the motion between two prescribed points with given velocities and the attainment of the given velocity. Two problems of the body motion in a forceless field were solved. Payloads are compared in the following cases: a) motion with constant thrust along the optimum power-off phase; b) motion with variable optimum propellant consumption along the power-off phase during the interval of time equal to that of the constant thrust phase; c) motion with variable optimum propellant consumption without power-off phases; d) motion along the power-on phases of a trajectory when the interval of motion time along these phases is a given part of the total motion time.

Section 11. In the light of Zander's ideas about using unnecessary items of structure as propellant we consider the problem of obtaining maximum payload at the active consumption of the used power source stages with a given factor of conversion of the used stages into propellant.

The results were as follows:

1°. At each instant of time the jet power (as in the case of constant power source weight) and the factor of conversion of the used stages into propellant should be as maximum as possible.

2°. The optimum curve of the power source weight variation consists of: the phase of constant weight; the phase of the power source weight and propellant storage proportional change; and the burnt-out phase where the thrust is generated by using as propellant the stages to be ejected.

3°. The optimum law of thrust acceleration as well as in Sections 1 and 6, should provide a minimum integral of the square acceleration.

4°. Active reduction in the power source weight yields an essential gain in the payload.

5°. Limit values of payload, corresponding to a continuous reduction in the power source weight may be approached, when this source of power has a relatively small finite number of sections.

Section 12. An optimal corrected thrust-acceleration program which gives a maximum value of the averaged payload in the case of the motion of a variable mass body with a constant power consumption is determined. A correlation function of occasional deflection from the thrust-acceleration program, and the dispersion of the measurement errors of the body attitude and velocity are assumed familiar. The optimum corrections to the thrust-acceleration program are chosen under the condition of a minimum integral of the square acceleration in case of motion from a measurement point to a given final point during the remaining period of time. Then the problem is reduced to the choice of such a distribution of the correction moments (the moments of redetermination of the acceleration program) and such a number of them, which should give a minimum averaged value of the integral increment of the square thrust acceleration provided that the trajectory is put into the given range of finite values.

By the example of the motion in a forceless field for a particular form of correlation function of the deflection from the thrust acceleration program it is shown that:

1°. In case of precise measurements the intervals between the correction moments form a geometrical progression and decrease to the end of the motion.

2°. For the precise measurements there is no optimal number of the correction moments, the increment of the functional being reduced with the number of the correction moments increasing.

3°. When there is dependence of the measurement error dispersion on the interval between the correction moments there must be an optimum number of the correction moments.

SUR LE MOUVEMENT D'UN CORPS VARIABLE AVEC LA DEPENSE CONSTANTE ET DIMINUEE DE LA PUISSANCE DANS LE CHAMPS DE GRAVITATION. PARTIE III.x)

Par Grodzovsky G.L.; Ivanov I.N., Tokarév V.V.

P.9. Ici on envisage le probleme de l'optimisation des paramètres du mouvement d'un corps de la masse variable avec la dépense limitée de la puissance dans la dépendance inélinéaire du poids de la source de la puissance de la grandeur de la puissance. On a établi que la propriété importante c'est à dire la division d'un problême de variation général sur deux particuliers: a) détermination de la grandeur optimum de la puissance on de la loi de sa diminution dans le temps et b) détermination de la loi optimum de la variation du vecteur de l'accélération allant de la poussé de réaction le long de la trajectoire - est gardée independamment de la forme de la dépendance fonctionnele entre la puissance et son poids. L'integral d'un carré de l'acceleration de la poussée de temps est général pour le deuxiême problême, comme pendant la dépendance fonctionnele linéaire. On a montré le criterium global du choix de la puissance optimum, on a donné une exemple pour le cas de la dépendance de degré entre la puissance et son poids.

P.10. Le problême global du mouvement d'un corps de masse variable avec le temps actif donné (avec la propulsion effective) est montré ici. L'introduction de la catégorie du temps actif donné permet définir des paramêtres quantitativfs du mouvement avec le temps limité de l'efficacité de la propulsion et donner aussi des résultats certains qualitatifs, independant d'une forme du champs de gravitation. Le poids de la propulsion doit etre constant car la diminution optimum du poids de la source de la puissance améliore peu les caractéristiques.

On a reçu des résultats suivants:

1. Comme en cas du temps optimum actif en programme optimum de la direction du vecteur de la poussée la puissance doit etre maximum possible dans les regions actives de la trajectoire independamment du caractêre de la programmie de la depense du combustible.

2. Les caracteristiques du mouvement changent en mal dans les regions avec la poussée zero sur la trajectoire avec la dépense optimum variable. Ainsi, l'accroissement du fonctionnal en venu de problême peut etre determiné pour la continuation donnée de la région passive en fonction des resultats du ce travil.

3. La déterioration des caracteristiques du probleme a lieu sur la trajectoire avec la poussée continue dans les régions passives.

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x) Parties I et II p. 1-8 Regardez les rapports faits aux XII et XIII congress de IAF.

4. Il est certain que en cas de la dépense optimum variable le choix de la correlation du poids entre la puissance et la réserve du combustible est le probleme independant des calculs de trajectoire; pendant la poussée constante les problemes de la determination de la trajectoire du poids sont réciproquement liés.

Pour les exemples des calculs donnés dans cette oeuvre la programme optimum de la direction du vecteur de la poussée et la relation optimum des poids de la source de la puissance et du combustible sont optimisées. Le paramètre (qui repond pour l'optimisation des poids pendant la poussée constante) est la relation de la depense du poids vers le poids original.

En role du fonctionnal du probleme on envisage la grandeur de la charge relative utile. On a étudié deux problemes de la dynamique: la déplacement d'un point de fixation de l'espace de phase en autre et acquisition du module donné de la vitesse. On a reçu des resolutions de deux probleme du mouvement dans le champs sans force. On a comparé les charges utiles aux cas suivants:

a) le mouvement avec la poussée constante et avec la region optimum passive.

b) le mouvement avec la depense optimum et avec la region passive dont la durée coinside avec la poussée constante.

c) le mouvement avec la dépense optimum variable sans les regions passives et

d) le mouvement avec les régions actives dont le temps sommaire compose les parties données des temps complets du transferement.

P.11. Dans la lumiète des idées de F.A. Zandere sur l'utilisabilité des éléments inutils de la construction en qualité du combustible on considère le problème de la charge maximum pendant la dépense active des étages de la source de la puissance avec le coefficient donné de la conversion des etages débrayant dans le combustible.

On a reçu les résultats suivants:

1. A tout le temps la puissance du jet (comme en cas du poids constant de la source) et le coefficient de l'utilisabilité de la partie débrayante de la source de la puissance en qualité du combustible doivent être possibles maxima.

2. La loi optimum du changement du poids de la source de la puissance se compose de la région du poids constant, de la region du changement proportionnel de la source et du reserve du combustible et de la région ou le réserve du combustible est dépensé et la poussée est crée par la conversion de la partie débrayant de la source de la puissance en combustible.

3. La loi optimum de l'accélération de la poussée (comme aux points 1,6) doit munir le minimum de l'integral de temp de cette accélérations carrée.

4. L'utilisabilité active de la puissance donne les avantages considerables dans la charge utile. Quand on aura enfine un nombre relativement petit des sections de la source de la puissance on pourra s'approcher des valeurs maxima de la charge utile qui correspondent a la diminution continue du poids de la source de la puissance.

P.12. On fait une édification du programme optimum compte tenu de la correction d'accélération de la poussée fournissant le maximum de la charge utile moyenne au cas du mouvement du corps de la masse variable avec la dépense de la puissance constante. On suppose, qu'on sait la fonction correlative des déflextions hasards du programme d'accélération de la poussée et les dispersions des fautes de la mesure de la situation et de la vitesse. Les corrections optima et le programme d'accélération de la poussée sont choisis de la condition de minimum d'integral d'accélération carrée au cas du mouvement de la position mésurée à'la position donnée finale dans le temps resté. Après cela le problème est ramené au choix d'une distribution définie des moments correctifs (c'est à dire les moments qui reconstruissent les programmes d'accélération) et du lour nombre. Il fault que ce choix fournirait le minimum de la valeur moyenne d'augmentation de l'integral d'accélération carré de la poussée à condition d'un coup de la trajectoire en domaine donné des significations finis.

Par une exemple du mouvement dans le champ sans forces pour l'aspect spécial de la fonction correlative du rejet du programme d'accélération de la poussée que:

1. Au cas des mesures precises les intervalles forment la progression géométrique entre les moments de la correction. Ceux-ci diminuent à la fin du mouvement.

2. Pour les mesures precises il n'y a pas du nombre optimum des moments de correction. L'accroissement du fonctionnal diminue avec l'augmentation du nombre des moments de correction.

3. Au cas d'existence de la dépendance des dispersions des erreurs en mesures d'un intervalle entre les moments des corrections le nombre optimum des moments de la correction doit exister.

ÜBER DIE BEWEGUNG EINES KÖRPERS VERÄNDERLICHER MASSE MIT KONSTANTEM UND VERMINDERNDEM LEISTUNGSAUFWAND IM GRAVIATIONSFELD

Grodzowsky G.L., Ivanow J.N., Tokarew W.W.
(1 and 2 Teile §§ 1-8 Siehe Vorträge , gehalten auf den 12 and 13 Tagungen der IAF)

Zusammenfassung

§-9. Es wird die Aufgabe über die Optimisierung der Parameter der Bewegung eines Körpers veränderlicher Masse mit dem begrenzten Leistungsaufwand bei der nichtlinearen Abhängigkeit des Gewichts eines Antriebssystems von der Leistung betrachtet.

Es ist festgestellt, dass die Einteilung des Gesamtvariationsproblems in zwei Teile:

a) Bestimmung der optimalen Leistung oder des Gesetzes ihrer Verminderung in Abhängingkeit von der Zeit und

b) Bestimmung des optimalen Gesetzes der Veränderung des Beschleunigungsvektors in Abhängigkeit vom Schub längs der Flugbahn

- sich unabhängig von der Art des Funktionalzusammenhangs zwischen der Leistung und dem Antriebssystems gewicht erhält.

Wie bei der linearen Funktionalabhängigkeit ist das Zeitintegral des Beschleunigungsquadrats des Strahlschubs für das zweite Problem massgebend.

Es ist das allgemeine Kriterium der Auswahl der optimalen Leistung angewiesen und ein Beispiel für den Fall des Potenzsatzes zwischen der Leistung und dem Gewicht angeführt.

§-10. Es ist die allgemeine Aufgabe über die Bewegung des Körpers veränderlicher Masse mit der vorgegebenen Flugdauer auf der Antriebsbahn betrachtet.

Die Einführung der Kategorie der vorgegebenen Flugdauer für die Phase der Antriebsbahn lässt, einerseits, die Qualitätsparameter der Bewegung mit der begrenzten Arbeitsfrist der Antriebsenergiequelle bestimmen und, andererseits, einige Quantitätsergebnisse erhalten die von der Art des Gravitationsfelds unabhängig sind.

Das Gewicht des Antriebssystems wird konstant angenommen weil die optimale Verminderung des Gewichts der Antriebsenergiequelle die Charaketristiken der Bewegung unbedeutend verbessert (siehe §-6).

Es sind folgende Ergebnisse erhalten:

N 1. Wie im Falle der optimalen Flugdauer für die Phase der Antriebsbahn soll bei dem optimalen Programm der Schubvektorsrichtung die Leistung den grösstmöglichen Wert auf der Antriebsbahn erhalten (unabhängig von der Art der Programmierung des Treibstoffverbrauchs).

N 2. Die Einführung der Phasen mit dem Nullschub in die Flugbahn mit dem veränderlichen optimalen Treibstoff-Verbrauch verschlechtert die Charakteristiken der Bewegung.

Die Vergrösserung des Funktionals der Aufgabe kann (auf Grund der Ergebnisse dieser Arbeit) für die gegebene Dauer des antriebslosen Fluges bestimmt sein.

N 3. Für die Flugbahn mit konstantem Schub bei den gegebenen antriebslosen Bahnabschnitten, die sich von den optimalen unterscheiden, kann man auch die Verschlechterung der Charakteristiken der Aufgabe berechnen.

§-4. Es ist bekannt, dass für den Fall des veränderlichen optimalen Treibstoffverbrauchs die Auswahl der optimalen Gewichtsverteilung zwischen der Leistung und dem Treibstoffvorrat auf die Aufgabe zurückzuführen ist, die von der Flugbahnberechnung unabhängig ist; bei konstantem Verbrauch (konstantem Schub) sind zwei Teiaufgaben: Flugbahn und Gewichtsberechnung in Zusammenhang zu behandeln.

Für die in der Arbeit angeführten Berechnungsbeispiele ist die Optimisierung nicht nur für das Optimalprogramm der Schubvektorsrichtung, sondern auch für das optimale Antriebsenergiequellen-Treibstoffagewichts-Verhaltnis durchgeführt.

Als Parameter für die Optimisierung der Gewichte beim konstanten Schub ist das Verhältnis des Massenverbrauchs zum Anfangsgewicht massgebend.

Als Funktional der Aufgabe wurde der Relativwert der Nutzlast betrachtet. Es wurden zwei Aufgaben der Dynamik untersucht: die Bewegung aus einem bestimmten Punkt des Phasenraumes in den anderen und die Auswahl des vorgegebenen Geschwindigkeitsmoduls. Es sind zwei Aufgaben über die Bewegung im kraftlosen Feld gelöst. Es wurde ein Vergleich der Nutzlasten für folgende Fälle durchgeführt: a) die Bewegung mit konctantem Schub und für optimalen autriebslosen Flugbahnabschnitt,

b) die Bewegung mit veränderlichem optimal em Massen verbrauch und für antriebslosen Flugabschnitt, der scienem Dauer nach mit der Flugdauer mit konstantem Schub übereinstimmt,

c) die Bewegung mit veränderlichem Optimalverbrauch ohne antriebslose Bahnabschnitte,

d) die Bewegung mit gegebener Flugdauer für die Phase der Antriebsbahn, wobei die Flugdauer angegebene Teile der Gesamten Flugdauer bildet.

§-11. Im Lichte von Zander's F.A. Ideen über die Ausnutzung von unnötigen Bauteilen als Treibstoff wird die Aufgabe über die maximale Mitzlast bei aktivem Verbrauch der Antriebsenergiequellenstufen mit vorgegebenem Koeffizienten der Ausnutzung der verbrauchten Stufen als Treibstoff behandelt. Es sind folgende Ergebnisse erhalten:

1. In jedem Zeitinterval sollen die Strahlleistung (wie auch beim konstanten Gewicht der Antriebsenergiequelle) und der Koeffizient der Ausnutzung der verbrauchten Antriebsenergiequellenstufen als Treibstoff den grösstmöglichen Wert orhalten.

2. Die optimale Kurve der Veränderung des Gewichts der Antriebsenergiequelle besteht aus dem Abschnitt konstanten Gewichts, dem Abschnitt proportionaler Veränderung zwischen dem Antriebsenergiequellengewicht und dem

Treibstoffvorrat und dem Abschnitt, auf dem der Treibstoffvorrat verbraucht ist und der Schub nur durch die Verwandlung der verbrauchten Antriebsenergiequellenstufen in Treibstoff erzeugt wird.

3. Das optimale Gesetz der Schubbeschleunigung, wie in Paragraphen 1,6 soll das Minimum des Zeitintegrals der Quadratbeschleunigung gewährleisten.

4. Der aktive Verbrauch der Antriebsenergiequellenstufen garantiert den wesentlichen Geweinn in Nutzlast.

5. Der Grenzwert der Nutzlast, welcher der kontinuierlichen Verminderung des Antriebsenergiequellengewichts entspricht, kann angenähert bei Verwendung von endlicher relativ kleiner Zahl der Energiequellenstufen erhalten werden.

§-12. Es ist ein mit Berücksichtigung der Korrektion optimales Schubbeschleunigungsprogramm aufgestellt, das den Höchstwert der mittleren Nutzlast bei Bewegung des Körpers veränderlicher Masse mit konstantem Leistungsaufwand gewährleistet. Es wird angenommen, dass die Korrelationsfunktion der zufälligen Abweichungen vom Schubbeschleunigungsprogramm und die Fehlerzerstreuung bei Messung der Position und Geschwindigkeit des Korpers bekannt sind.

Die optimalen Korrektionen und das Programm der Schubbeschleunigung werden aus der Bedingung des Integrals-minimums vom Beschleunigungsquadrat bei Bewegung aus gemessener Position in vorgegebene endliche Position während des Zeitrestintervals ausgewählt.

Danach wird die Aufgabe auf die Auswahl solcher Korrektionsmoment-Verteilung (Momente der Veränderung des Beschleunigungsprogramms) und solcher Korrektionsmomentzahl zurückgeführt, die das Minimum des Mittelwertes des Inkrements des Integrals vom Quadrat der Schubsbeschleunigung garantieren könnten, unter der Bedingung, dass die Bahn ins vorgegebene Gebiet endlicher Werte gelangt.

Es ist an einem Beispiel der Bewegung im kraftlosen Feld für die spezielle Form der Korrelationsfunktion der Abweichungen vom Schubbeschleunigungsprogramm gezeigt, dass

1. bei genauen Messungen die Korrektionsmomentintervalle die geometrische Progression bilden, woßei diese Intervalle zum Ende der Bewegung kürzer werden;

2. es für genaue Messungen keine optimale Korrektionsmomentzahl gibt, und das Funktional-Inkrement mit der Vergrösserung der Korrektionsmomentanzahl abnimmt;

3. bei Bestehen der Abhängigkeit der Messfehler-Zerstreuung vom Korrektionsmoment-Intervall die optimale Korrektionsmoment-anzahl vorhanden sein soll.

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A FEW PROBLEMS OF PHYSIOLOGY OF CIRCULATION DURING WEIGHTLESSNESS

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ABSTRACT

Responses of the cardiovascular system to the action of weightlessness are of phasic character. Three phases are distinguished: transition phase, phase of incomplete adaptation and phase of relatively stable adaptation.

Changes in the functional state of the cardiovascular system are presumably brought about by:

- decrease in the muscular activity during weightlessness;
- change in the nervous regulation of the circulatory system, in particular by relatively increased influence of the vagus system;
- development of asynchronism greater than on the earth in the action of the right and left parts of the heart.

Maintenance of an adequate functional level in the circulatory system is very important to assure good performing ability of space pilots during a prolonged flight and to provide their safe return under conditions of normal gravitation. Investigations of this problem is of great practical significance for astronautics.

Among space flight factors, weightlessness is of particular interest. Unfortunately, experiments with water immersion or prolonged hypokinesia provide very indirect data for the study of various effects of weightlessness upon living organisms. Therefore, biomedical experiments carried out on spaceships are of great interest, first of all for investigating physiological aspects of weightlessness.

Theoretical examination of possible physiological shifts during weightlessness suggest regulatory responses of various origin and character aimed at the adaptation of the organism to the new physical environmental conditions.

Since the muscular system ought to make less of an effort to perform the same job under weightlessness as compared to that on the ground, the general level of metabolism during weightlessness can be expected to be reduced. In its turn, the reduced energy requirements will affect the activity of the cardiovascular system inasmuch as the reduced oxygen requirements of tissues of the living organism will bring about a decrease in the minute volume and other circulatory parameters (13, 17).

On the other hand, changes in the relationships between afferent systems, particularly changes in pulsation from proprioceptor muscles and receptor zones of the vestibular apparatus, ought beyond doubt to affect the nervous regulation of the cardiovascular system. Therefore, afferent changes can also account for a number of shifts in the functional state of cardiovascular system under weightless conditions (7, 9).

And finally, the emotional stress accompanying space flight should also be taken into account. This factor can exert an essential effect on the activity of higher vegetative centers and thus on the circulatory regulation.

In summing up, three main theoretically possible reasons accounting for changes in the circulatory system during orbital space flight can be indicated: 1) general decrease of energy requirements of the organism, 2) changes in the nervous regulation (afferentation), and 3) emotional stress. It is possible that some other reasons will be disclosed in the future but today discussion of experimental data can be done only on the basis of the above statements.

Soviet biomedical investigations in outer space have provided ample experimental information on the significance of the circulatory system in the responses of living organism to unusual weightless conditions (2, 12, 14). The present communication is an attempt to systematize the data obtained and to outline further investigations with the purpose of illuminating the role of the circulatory system in the organism adaptation to the weightless state. It is understood that critical study of the conceptions presented will be the source of new ideas and experiments in this field.

Methods

Investigations were carried out on board Soviet space ship-satellites 2 and 5 and spaceships "Vostok". The following cardiological methods were employed: electrocardiography, phonocardiography, seismocardiography, kinetocardiography, sphygmography and arterial oscillography (1, 3, 4, 5). Modifications of a number of previously known clinical methods as well as the development of new ones became necessary for space flight conditions. Seismocardiography is, in particular, a new variety of ballistocardiography. It was used for the first time in outer space investigations and will evidently find further extensive and successful employment in medicine. The amplitude and duration of systolic and diastolic cycles of a seismocardiogram indirectly reflect the state of the myocardial contractile function. With the purpose of a more economic usage of telemetric channels a method of "integral" phonocardiography was developed, the method involving detection and integration of output signals. In order to secure prolonged and qualitative recordings of ECG under space flight conditions special ways of arranging of biopotential leads and methods of long-term electrode fixation were elaborated.

Results

Experimental data are summarized in Tables 1, 2 and 3. The material given shows a certain dynamics in the indices of cardiac activity. After being sharply elevated at the action phase of the flight the pulse rate returns to normal during the initial period of weightlessness. The normalization of pulse rate is of individual character but in all case it takes place considerably more slowly than after laboratory centrifuge runs.

Three ways of pulse rate normalization can be distinguished in dogs: 1) slow normalization - Mushka; 2) rapid normalization with the development of relative bradycardia - Strelka, Pchyolka; 3) rapid normalization without accompanying bradycardia - Belka. Similar changes were observed in the cosmonauts. However, it is really difficult to give a correct estimation of the degree of the reaction in human subjects because of differences in the emotional status. G.S. Titov revealed the slowest pulse rate normalization. In the course of many-day weightless state the dynamics of pulse rate appeared to be related to the diurnal cycle. In addition to that, on the morning of the first 2 or 3 days tachycardia was observed, being mostly pronounced in V.V. Tereshkova. It should also be noted that during the night sleep almost all cosmonauts showed a lower pulse rate than during laboratory space flight simulation experiments.

Special attention was paid to variations in pulse rate. In the norm, dogs are known to show a distinct arhythmia which amounts to 0.8 sec (i.e. the difference between the maximal and minimal values of the duration in the cardiac cycle). Greater requirements being made to the circulatory system, the pulse arh thmia decreases or even disappears. The similar picture can be observed upon the action of overloads at the active span of the flight. Under weightless conditions arhythmia is quickly restored and reaches values exceeding those achieved on earth. As known, people do not reveal a distinct pulse arhythmia under normal conditions. The difference in the duration of the cardiac cycle does not usually exceed 0.20 to 25 sec under rest conditions. During space flight the cosmonauts showed considerably greater difference in the duration of cardiac cycles amounting to 0.5 to 0.7 sec.

The auriculo-ventricular conduction time during weightlessness can be both shorter (the dog Belka) and longer (the dog Pchyolka) as compared to that of pre-launch. Mushka retained the pre-launch value. As to Strelka, its conduction time was somewhat longer in the first half of the flight and shorter in the second one. The auriculo-ventricular conduction time shown by the cosmonauts was moderately longer than on the earth. The diurnal changes associated with the index were of interest. In the morning it was shorter in V.F. Bykovsky and V.V. Tereshkova, while it was comparatively longer in A.G. Nikolayev and P.R. Popovich.

Intraventricular conduction during weightlessness exhibits no noticeable changes either in human subjects or in animals.

The duration of electric systole after reduction at the active flight span comparatively increases during the initial period of weightlessness. By the end of the first 24 hours of flight the duration of the electric systole in animals becomes somewhat shorter than before take-off while in people it becomes somewhat longer. Thereby the systole appears shorter in the morning. Great importance is attached to the systolic index, i.e. the ratio of the duration of the electric systole to that of the cardiac cycle (11). The systolic cycle in animals during weightlessness appeared moderately shorter than on the ground. As to cosmonauts, their systolic index changed differently. In the morning A.G. Nikolayev, P.R. Popovich and V.V. Tereshkova showed its increase while V.F. Bykovsky, on the contrary, showed its decrease.

The duration of mechanical systole was determined by means of phono- and kinetocardiograms. In general, the duration of the mechanical systole decreased at the beginning of orbital flight, then it increased and finally, by the end of the first 24 hours it fell below initial values. Of interest is the ratio of the durations of the mechanical and electrical systoles (mechanoelectrical coefficient - K). The data presented show that changes in the mechanical systole are more pronounced in comparison to the electrical one. Therefore the K-coefficient is relatively shorter during long-term action of weightlessness than at the onset of the orbital flight.

Electromechanical delay (i.e. the lapse of time between the ECG Q-wave and the onset of the mechanical systole) as derived from kinetrocardiographic studies made during G.S. Titov's flight, sharply extends after 5 to 8 hour stay under weightless conditions.

Arterial blood pressure was taken under study during the dog Strelka's flight. Arterial pressure changes during weightlessness in the following way. At the initial period a twofold reaction can be observed: the systolic pressure falls by 50 to 80 mm. Hg as compared to that at the active phase of the flight and by 35 to 30 mm Hg as compared to pre-launch values. Then a certain rise in the maximal pressure takes place, though it does not reach pre-launch values it is accompanied by the reduction of diastolic and elevation of pulse pressures. Beginning with the second circuit (revolution around the earth), i.e. 1.5 to 2 hours after launching, stable hypotonia can be observed. Maximal pressure appears to be 40 to 50 mm. Hg lower than during the pre-launch period. After the sixth circuit the pressure begins to rise reaching the values observed at the active span. From the thirteenth circuit up to the onset of descent the maximal pressure was steadily 10 to 30 mm. Hg below the initial one. Diastolic pressure was also lower than the initial one while the pulse pressure remained close to the initial one.

<u>The contractile ability of myocardium</u> could be studied in our experiments in an indirect way only. Important data were provided by seismocardiogram, particularly by the first cycle where the amplitude was proportional to the cardiac output. As indicated in Table 2, during weightlessness the animal showed an absolute and relative increase of the first cycle of seismocardiogram. It can be best seen beginning from the seventh circuit. Seismocardiographic investigations carried out onboard spaceships "Vostok" also disclosed an initial relative rise in the first cycle of seismocardiogram. However, after 2 to 3 day stay in weightlessness the difference between the amplitudes of the first and second cycles lessens. It may be associated with the absolute increase in the amplitude of the second cycle which mainly repulses the "reverse" hydraulic flow of the blood. The amplitude of the second cycle depends on elastic properties of large vessels and the level of arterial pressure. In this connection it is interesting to mention the phenomenon observed during V.V. Tereshkova's flight. By the end of the flight the third cycle of seismocardiogram appeared and was noticed for a few seconds. According to ECG no

changes in automatism, excitability or conduction were observed. Thus, the appearance of the third cycle is apparently connected with the changes in intracardiac hemodynamics. The third cycle may be brought about by an extremely intensive filling of ventricles at the diastolic phase.

Coordination of cardiac contractions is an important sign characterizing the functional state of myocardium. As known, the action of the right and left parts of the heart is in the norm strictly determined in volume and time. Even small disorders in the correlation lead to changes in the duration of seismocardiographic cycles, as well as in the intensity and duration of phonocardiographic tones. As indicated in Table 2 the animals show: 1) increased intensity of the first tone of phonocardiogram at the sixth or seventh circuit (the dog Belka); 2) increased intensity and duration of the second tone of phonocardiogram; 3) initial reduction (at the second or third circuit) with the further stable extension of the first cycle of seismocardiogram.

According to seismocardiographic investigations cosmonauts V.F. Bykovsky and V.V. Tereshkova showed prolonged duration of both cycles during the second of third day of their flight. Thus, there are objective data indicating that under weightless conditions the cardiac activity changes in agreement with variations occuring in time and amplitude relationships between forces generated by the right and left parts of the heart. Proceeding from clinical observations, the rise in the intensity and duration of the second tone of phonocardiogram can be interpreted as the enhancement and delay of the pulmonary component of the second tone in comparison with the aortic one (10). The extension of seismocardiographic cycles can be the result of higher than normal asynchronism, occurred in the action of the right and left parts of the heart.

The above data make it possible to distinguish the following three phases in the responses of the cardiovascular system to the effect of weightlessness.

1. The transition phase, which involves changes brought about mainly by the after-effect of accelerations that affected the organism during the boost period. This phase is characterized by fall of pulse rate and rise of pulse arhythmia in animals and pulse variations in human beings. No pronounced shifts in other indices have been noticed.

2. The phase of incomplete adaptation to weightlessness which lasts for 10 to 12 hours. The following changes have been observed during this period. The pulse rate gradually returns to normal. The time of auriculo-ventricular conduction becomes longer. The duration of electric systole also becomes somewhat longer. The mechanical systole becomes at first shorter but then longer. The arterial blood pressure steadily falls but shows a short-term elevation at the end of the phase. The first cycle of seismocardiogram becomes shorter. According to phonocardiography animals show a rise in the intensity of both tones and a sharp elongation of the second tone.

3. The phase of relatively stable adaptation to weightlessness. At the phase almost all indices of the cardiovascular system taken under study show pronounced changes. The pulse rate before launching becomes somewhat lower. The time of auriculo-ventricular conduction becomes longer. The diurnal cycle apparently affects the auriculo-ventricular conduction, electric systole and systolic index. The duration of mechanical systole shortens and the mechano-electrical coefficient decreases. Electromechanical delay becomes longer. Animals show a pronounced extension of the first cycle of seismocardiogram. Cosmonauts show that after the initial increase, it gradually disappears by the second or third day of the flight. Both humans and animals show a stable extension of the first and second cycles of seismocardiogram.

Thus, basing on the experimental data obtained, it proved possible to reveal a number of specific changes in the functional state of the circulatory system associated with weightlessness effects. In addition, it became possible to classify the changes into phases in relation to the time of flight.

Discussion

The study of experimental information presented indicates that responses of the cardiovascular system to the action of weightlessness are of a complicated character. First of all, they are phasic changes. Most interesting are the phases of incomplete adaptation and relatively stable adaptation to weightlessness.

After the second or third circuit (i.e. after 2 to 4 hours) certain shifts in various indices of the cardiovascular system can be observed, e.g. pulse rate, arterial blood pressure, heart tonicity, etc. They are, evidently, the result of the influence of weightlessness. Attention should be paid first of all to the "unloading" character of the changes observed. Such changes as the fall of systolic and diastolic pressure, relative decrease of pulse rate, reduction of mechanical and electric systoles can be brought about by the reduction of cardiac output. Reduced requirements for energy to provide the muscular activity during weightlessness account themselves for fewer demands made by various tissues of living organism to the cardiovascular system. Besides, the disappearance of hydrostatic factor and blood "weight" also makes the cardiac action appreciably easier. The increase in the amplitude of the first cycle of seismocardiogram and reduction of the mechanical systole indicate that the rate of the blood removal by the ventricles is increased while the time shortens. And this is quite understandable since the reduction of the minute volume and arterial blood pressure should lead to a greater rate of removal during the shorter time provided that the same contractile ability of myocardium retains.

In the course of the functional reorganization of cardiac activity the circulatory system gradually adapts itself to the new physical conditions. Thereby the phase of incomplete adaptation is replaced by the end of the first day by the phase of relatively stable adaptation. The autonomic nervous system plays evidently a significant role in the realization of adaptive reactions (15, 16). It is suggested that the action of weightlessness causes the effect of the parasympathetic system on cardiac activity to increase while that of sympathetic one decreases. This is evidenced by the lengthening of auriculo-ventricular conduction, by relative bradycardia, and by fall of the arterial pressure. The study of pulse arhythmia in animals and heart rate variation in humans is very interesting. It is well known that arhythmia found in dogs under rest conditions disappears upon atropine administration. Therefore, arhythmia depends on whether parasympathetic influences prevail. It can be suggested that arhythmia will be more pronouncedly expressed in dependence with the greater extent of predomination of the vagus system over the sympathetic one. The sinus arhythmia in human beings is also connected with the predomination of the parasympathetic system.

The above data testifying to the predominating influence of the vagus system during weightlessness are in good agreement with the phenomena of demobilization of cardiac activity and "unloading" reaction which reflects processes of adaptation occurring in the organism in view of smaller energy requirements and lower intensity of muscular metabolism. It is well known that the rise in the functional activity of organs and tissues, as well as the increased intensity of metabolism are connected with excitation of the sympathetic nervous system (8), while their decrease is, on the contrary, the result of predominating parasympathetic influences. Thus, a distinct regulatory mechanism of the adaptation of the circulatory system to weightlessness can now be outlined. It involves changes in the nervous regulation of cardiac activity and decrease of the total cardiac output.

It should be however noted that the adaptation of the cardiovascular system to new environmental conditions is but relatively stable. It is interesting to mention the response shown by almost all cosmonauts to the sleep - vigilance transition which included a short-term rise in pulse rate (with a fall to follow) and decrease or increase of the systolic index, of the time of auriculo-ventricular conduction and shortening of electric systole. The changes mentioned give evidence to the appearance of short-lived sympathetic effects against the predomination of the para-sympathetic system. These changes on the part of the sympathetic nervous system can be cortically determined and connected with emotional stress or orienting reflex while awakening.

There are facts that cannot be so far interpreted from the point of view of the above conceptions. They are: 1) extension of both cycles of seismocardiogram, increase of the time of electromechanical delay, rise in the intensity and duration of the second tone of phonocardiogram. All these phenomena can be associated with the changes in time correlation between the forces generated by the right and left parts of the heart. This raises the question of the reasons underlying the phenomena. The difference in the working regime between the right and left parts of the heart can be caused, for instance, by the difference in pressures in systemic and pulmonary circulation. The occurrence during weightlessness of ventricular asynchronism, higher than in the norm, of certain disturbances in usual coordination of cardiac contractions cannot be so far convincingly explained on the basis of the data accumulated. It needs further purposeful study of the circulatory system under space flight conditions.

While estimating the responses of the cardiovascular system to a prolonged action of weightlessness it is of greatest practical significance to determine probable tolerance limits to decelerations. The reduction of the total cardiac output, regulatory reorganization of the cardiovascular system with the aim to meet the requirements of the new functioning level will undoubtedly "disadapt" myocardium and consequently it will be a serious task for it to endure great stresses of the re-entry. Thus various unfavourable reactions can be expected to appear during descent. The object of physiological investigations is to elucidate the degree of the heart "disadaptation" resulting from a prolonged action of weightlessness and to determine various possible disturbances in the cardiac action during re-entry. Therefore, the study of physiology of the cardio-vascular system during weightlessness is very important in securing safe long-term space flights and return of the crew to earth.

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Table 1

Dynamics of ECG indices and of arterial blood pressure shown by animals in weightlessness (average values)

Indices	Animals	Pre-launch	Circuits									
			2	3	4	5	6	7	13	14	15	16
1	2	3	4	5	6	7	8	9	10	11	12	13
Pulse rate (beat/min)	Strelka	71	69	70	75	79	88	113	121	101	117	88
	Belka	62	70	69	74	61	130	136	85	71	93	74
	Pchyolka	70	88	86	74	71	80	77	80	66	58	67
	Mushka	66	167	115	103	100	92	192	103	80	95	87
Pulse arhythmia (sec)	Strelka	0.48	0.83	0.83	0.67	0.70	0.39	0.19	0.14	0.36	0.22	0.45
	Belka	0.73	0.88	0.97	0.73	0.95	0.16	0.26	0.60	0.72	0.40	0.64
	Pchyolka	0.23	0.37	0.42	0.59	0.64	0.41	0.47	0.44	0.72	0.76	0.60
	Mushka	0.16	0.06	0.26	0.42	0.43	0.51	0.42	0.35	0.58	0.40	0.46
Auriculo-ventricular conduction (sec)	Strelka	0.11	0.11	0.13	0.11	0.10	0.10	0.09	0.09	0.08	0.10	0.10
	Belka	0.12	0.10	0.11	0.11	0.10	0.08	0.09	0.08	0.08	0.08	0.10
	Pchyolka	0.12	0.12	0.11	0.13	0.13	0.10	0.11	0.09	0.13	0.14	0.12
	Mushka	0.10	0.08	0.10	0.10	0.11	0.10	0.10	0.09	0.10	0.10	0.10
Intraventricular conduction (sec)	Strelka	0.07	0.06	0.07	0.08	0.08	0.03	0.08	0.09	0.08	0.06	0.07
	Belka	0.06	0.06	0.03	0.05	0.06	0.05	0.05	0.07	0.07	0.06	0.06
	Pchyolka	0.10	0.11	0.09	0.09	0.10	0.03	0.10	0.05	0.06	0.07	0.07
	Mushka	0.06	0.07	0.06	0.08	0.08	0.03	0.07	0.07	0.08	0.08	0.07

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Table 1 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	3
Electric systole (sec)	Strelka	0.28	0.25	0.24	0.23	0.24	0.23	0.25	0.25	0.25	0.32	(29
	Belka	0.27	0.27	0.30	0.29	0.25	0.22	0.25	0.28	0.27	0.24	(24
	Pchyolka	0.28	0.21	0.20	0.21	0.20	0.20	0.21	0.20	0.22	0.22	(22
	Mushka	0.24	0.20	0.23	0.23	0.23	0.24	0.24	0.23	0.24	0.26	(24
Systolic index (per cent)	Strelka	42	28	28	29	31	34	48	51	41	43	3
	Belka	36	31	28	29	24	65	50	54	28	39	9
	Pchyolka	36	31	29	26	23	27	27	27	24	21	5
	Mushka	47	57	45	40	39	35	38	39	34	41	6
Maximal arterial pressure (mm.Hg)	Strelka	140	92	99	96	100	198	181	128	112	120	1 9
Minimal arterial pressure (mm.Hg)		51	43	43	34	36	37	48	45	30	43	1

Table 2

Dynamics of phonocardiographic and seismocardiographic indices shown by animals in weightlessness

Indices	Animals	Pre-launch	Circuits									
			2	3	4	5	6	7	13	14	15	16
1	2	3	4	5	6	7	8	9	10	11	12	13
Amplitude of 1st tone of PhCG (mm)	Belka	1.9	1.6	2.2	1.7	2	3	2.8	1	1.9	2.2	1.8
	Mushka	1.4	2.7	1.5	1.7	1.3	1.3	1.3	1.1	1	1	1
Amplitude of 2nd tone of PhCG (mm)	Belka	1.3	2.5	2.7	2.2	2	3	2.1	0.8	2.7	2.3	1.8
	Mushka	1.1	4.4	1.2	1.3	1.1	1.3	1.4	0.9	0.7	1	0.9
Duration of 1st tone of PhCG (sec)	Belka	0.1	0.1	0.1	0.11	0.12	0.12	0.08	0.07	0.10	0.09	0.1
	Mushka	0.09	0.20	0.08	0.09	0.11	0.09	0.09	0.12	0.1	0.08	0.09
Duration of 2nd tone of PhCG (sec)	Belka	0.05	0.06	0.07	0.07	0.08	0.09	0.07	0.05	0.08	0.07	0.08
	Mushka	0.07	0.12	0.1	0.09	0.14	0.10	0.08	0.1	0.09	0.08	0.08
Mechanical systole (sec)	Belka	0.24	0.18	0.19	0.19	0.19	0.18	0.15	0.18	0.18	0.18	0.18
	Mushka	0.18	0.20	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.17	0.16
Mechanoelectric coefficient - K	Belka	0.88	0.83	0.70	0.83	0.88	0.90	0.8	0.82	0.82	0.85	0.82
	Mushka	0.75	1.0	0.67	0.66	0.7	0.7	0.7	0.7	0.7	0.64	0.66
Amplitude of 1st cycle of seismocardiogram (mm)	Pchyolka	7	7	8	6	9	7	9	8	9	10	8
Amplitude of 2nd cycle of seismocardiogram (mm)	Pchyolka	7	6	5	6	9	6	6	6	7	7	5
Duration of 1st cycle of seismocardiogram (sec)	Pchyolka	0.17	0.16	0.15	0.21	0.21	0.29	0.41	0.27	0.18	0.19	0.2

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Table 3

Dynamics of several indices of the circulatory system shown by cosmonauts in weightlessness (average values)

Indices	Cosmonauts	Pre-launch	Circuits 7	13	23	29	39	45	55	61	71	76
1	2	3	4	5	6	7	8	9	10	11	12	13
Auriculo-ventricular conduction (sec)	Titov G.S.	0.16	0.16	0.16	–	–	–	–	–	–	–	–
	Nikolayev A.G.	0.10	0.12	0.11	0.10	0.12	0.11	0.12	0.12	0.12	–	–
	Popovich P.R.	0.10	–	0.10	0.13	0.13	0.12	0.13	–	–	–	–
	Bykovsky V.F.	0.10	0.12	0.08	0.11	0.08	0.12	0.07	0.11	0.07	0.11	0.07
	Tereshkova V.V.	0.11	0.08	0.07	0.11	0.07	0.08	0.07	–	–	–	–
Electric systole (sec)	Titov G.S.	0.40	0.31	0.36	0.34	–	–	–	–	–	–	–
	Nikolayev A.G.	0.36	0.36	0.38	0.32	0.38	0.34	0.38	0.37	0.33	–	–
	Popovich P.R.	0.37	–	0.39	0.41	0.40	0.40	0.39	–	–	–	–
	Bykovsky V.F.	0.38	0.37	0.35	0.41	0.36	0.41	0.32	0.40	0.38	0.40	0.38
	Tereshkova V.V.	0.38	0.36	0.35	0.40	0.35	0.34	0.37	–	–	–	–
Systolic index (per cent)	Titov G.S.	46	49	49	–	–	–	–	–	–	–	–
	Nikolayev A.G.	38	49	47	41	40	40	45	37	42	–	–
	Popovich P.R.	37	–	41	37	41	38	39	–	–	–	–
	Bykovsky V.F.	40	36	35	48	33	42	32	49	33	39	30
	Tereshkova V.V.	47	53	58	44	55	47	41	–	–	–	–
Electromechanical delay	Titov G.S.	0.033	0.048	0.046	–	–	–	–	–	–	–	–
Mechanical systole (sec)	Titov G.S.	0.35	0.47	0.41	–	–	–	–	–	–	–	–

Table 3 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13
Duration of 1st cycle of seismo-cardiogram (sec)	Bykovsky V.F.	0.14	-	0.10	0.06	0.08-0.15	0.15	0.13	0.17	0.17	0.18	0.19
	Tereshkova V.V.	0.13	-	0.12-0.16	0.16	0.11-0.17	0.12	0.14	-	-	-	-
Duration of 2nd cycle of seismo-cardiogram (sec)	Bykovsky V.F.	0.07	-	0.05	0.04	0.07	0.08	0.09	0.10	0.12	0.07	0.09
	Tereshkova V.V.	0.07	-	0.08	0.10	0.06	0.09	0.06	-	-	-	-
Ratio A1/A2 of seismocardiogram	Bykovsky V.F.	2.5	-	3	1.6	1.6	2	2.7	2.8	2.5	2.8	2.4
	Tereshkova V.V.	1.8	-	1.6	1.5	2.0	3.5	3.5	-	-	-	-

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INVESTIGATION OF BIOLOGICAL EFFECT OF COSMIC RADIATION UNDER CONDITIONS OF SPACE FLIGHT

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ABSTRACT

The present communication summarizes results of radio-biological investigations conducted on seven Soviet ships-satellites (ships-satellites 2,4, and 5 and Vostoks 1,2,3, and 4). For the study of the injuring effect of cosmic radiation, objects were used which possessed different radiosensitivity and tests were performed reflecting changes in physiological functions and in hereditary structures of a cell, an organism. Experiments were conducted on mammals (dogs, mice, rats, guinea pigs), fruit flies, plant objects-seeds of higher plants (wheat, pea, onion, pine, beans, raddish, carrot, etc.), Tradescantia microspores, culture of chlorella algae on different nutrient media, numerous biological and cytological objects on tissue, cellular, subcellular and molecular levels.

Analysis of experimental results has shown that under the influence of cosmic radiation in a totality with other flight factors in hereditary structures of different biological objects - cells of the marrow of mice, seeds of different plants, lysogenic bacteria, Tradescantia microspores, etc. - disturbances appear which have a small, but statistically confident value. At the same time it has been established that cosmic radiation caused no stable and expressed changes in life functions of mammals and man.

Investigation of the biological effect of cosmic radiation is one of the complicated and at the same time most urgent problems of cosmic biology and medicine.

Successes of science and rocketry have made it possible to accumulate by the present time relatively extensive data on physical parameters of cosmic radiation - its composition, intensity, the energy spectrum and spatial distribution in circumterrestrial space.

According to present data, cosmic radiation is represented by galactic rays (primary cosmic radiation), by protons produced during solar flares and by penetrating radiation of circumterrestrial belts. Due to difficulty of protection, of practical interest is the biological effect of high-energy protons and heavy nuclei of galactic radiation (long-term flights), protons of solar flares and the inner radiation belt with energies of about 100 and more Mev.

Investigation of the biological effect of cosmic radiation and its individual components is conducted under conditions of flight experiments on various flying vehicles and in laboratory experiments with the use of proton accelerators and more heavy particle accelerators. It is quite evident that both methods of investigation, which have its advantages and drawbacks, should complement each other. Let us consider briefly these two trends.

At present time in some countries, including the USSR, there are technical possibilities for conducting laboratory investigations of the biological effect of protons - the predominant type of radiations in outer space. However, conditions of irradiation by protons at different accelerating installations considerably differ from those which can be encountered in flight. The impulse character of irradiation and large dose rate obtained in experiments with protons at accelerators certainly affect the results of the biological effect of radiation which should be taken into account at the estimate of biological effectiveness of protons of primary cosmic radiation, of the inner radiation belt and solar flares. Much less are biologists' opportunities for studying the biological effect of high-energy heavy nuclei in laboratory conditions.

The successes in the development of rocketry and aeronautics have created the necessary conditions for carrying out radiobiological investigations in flight experiments. For these purposes high-altitude balloons-aerostats, rockets, recovered artificial Earth satellites are used.

During flight biological objects carried on board ships-satellites are subjected not only to the effect of cosmic radiation, but of other factors too - accelerations, vibrations, weightlessness, etc. Therefore, if we fail to protect the organism from these factors, and ionizing radiation acts in a complex or against the background of their influences, then difficulties naturally arise in the estimate of the radiobiological effect.

The influence of flight dynamical factors is absent during experiments at high-altitude balloons. It is more rational to use balloons for studies of the biological effect of the heavy component of cosmic radiation lifting them to heights of 35-40 km. However, at these heights shields in the form of the Earth's magnetic fields and the layer of the atmosphere prevent us from studying the entire spectrum of heavy particles encountered in outer space.

The first experiments on a high-altitude balloon were conducted with this aim in view by the Soviet scientist G.G. Frizen in 1935 /1/. The main task of his experiment was to study, on fruit flies, the role of cosmic radiation in spontaneous mutation. The exposure of the objects took place at a height of 15,900 meters during two hours. The experimenter did not detect the harmful effect of cosmic radiation and made a conclusion that apparently cosmic radiation could not be considered an evolution factor for earthly organisms. The same year experiments on aerostats were begun in the USA too. Extensive use of aerostats for biological purposes has been made since 1951. The height and duration of flight were extended: aerostats could be lifted up to 30 km and flew during approximately 24 hours. Experiments were conducted on various biological objects: fruit-flies, seeds of different plants, neurospores, mice, guinea-pigs, etc. (Simons 2; Simons and Hewitt 3; Pipkin and Sullivan 4; Eugster and Simons 5). At the same time physical characteristics of cosmic radiation were investigated, such as density of particle flux, charge and energy of particles, etc.

Analyzing the results of American investigations conducted on high-altitude balloons one should emphasize that in the predominant majority of experiments no injuring effect of cosmic radiation was revealed. Effects which can be ascribed to the action of cosmic radiation were revealed only in experiments on barleycorn (Eugster and Simons 5), cells of man's skin (Eugster 6) and in experiments on black mice of the line C_{57}bl. (Chase 7, Simons and Steinmetz 8). In experiments on barleycorn the appearance of mutations was revealed - short-sized and ugly forms in the next generation of these grains. After-flight observations of black mice revealed an increase of the number of grey hair, and also the fact that in some cases grey hair was situated on one line as if along the track of heavy particles of cosmic radiation. The appearance of pigmentized spot was revealed in a human skin strip. Eugster associated this with the effect of a heavy particle.

The absence of the influence of cosmic radiation on hereditary structure and physiological functions in different objects in the majority of experiments should be explained first of all by insufficient height and small duration of the exposure of biological material.

In flight experiments conducted by Soviet and American investigators at high-altitude and ballistic rockets flight altitude was increased considerably. However, time of exposure of biological objects continued to be insufficient. In these tests, as in the majority of balloon experiments, it was impossible to detect and estimate the biological effect of cosmic radiation (Yazdovsky V.I. et al. 9, Graybiel et al. 10).

The possibilities of radiobiological investigations extended considerably with the use of Earth satellites for these purposes. The historic flight of the dog Laika opened the series of these experiments.

In the present communication results of radiobiological investigations conducted on seven Soviet spacecrafts (ships-satellites 2,4, and 5 and ships Vostok 1,2,3, and 4) are discussed. For studies of the injuring effect of cosmic radiation, objects having various radiosensitivity were used. Tests reflected changes in physiological functions and hereditary structures of a cell, of an organism.

Mammals (dogs, mice, rats, guinea-pigs), fruit flies, plant objects-seeds of higher plants (wheat, pea, onion, pine, beans, radish, carrot, etc.), microspores of Tradescantia, chlorella algae cultures on different nutrient media, numerous biological and cytological objects at tissue, cellular; subcellular and molecular levels were used in these experiments (Gyurdzhian A.A. 11, Antipov V.V. et al. 12).

In experiments on mammals special attention was given to the study of the state of the blood production system, to the determination of intermediate exchange products of nucleic acids (desoxycytidine and Dishe of positive substances), to the investigation of the state of natural immunity, and to the determination of the content of serotonin in blood. Besides, control was conducted over the state of pigmentation of hair of black mice (line C57bl.). Physiological changes were investigated on other objects too, such as seeds of higher plants, microorganisms, cells of different tissues in the culture, etc.

The effect of ionizing radiation on hereditary structures of a cell, of an organism was studied on mice, fruit flies, seeds of higher plants, lysogenic culture of E. coli, microspores of Tradescantia paludosa, etc.

The abovementioned biological objects were in flight from 1.5 to 96 hours at heights of 180-320 km. The total radiation dose received for the period of flights was respectively from 1.5 (during 1.5 hour flight) to 60 mrad (during 96-hour flight) at average dose rate from 7.2 to 13.2 mrad per 24 hours. At these heights at the orbital inclination of 65° about 90% of the absorbed dose is caused by primary cosmic radiation, and 10% is due to the Earth's radiation belts (Nesterov V.E. et al.13).

Taking into account biophysical peculiarities of the heavy component of galactic rays one may think that biological effectiveness of radiation of this type will be considerably higher than effectiveness of X-rays and gamma-rays. It is also evident that being sensitizers of ionizing radiation, some flight factors intensify the effect of this radiation. Consequently, even if these peculiarities were taken into account one could expect that radiation reaction would be discovered in some biological objects - lysogenic bacteria, fruit flies, Tradescantia microspores.

What are the results of these experiments and how do they agree with the readings of physical dosimeters?

General clinical observations and special laboratory studies of peripheral blood, marrow, urine, the state of natural immunity of mammals which flew on orbital ships did not reveal any indices of radiation injury (A.A. Gyurdzhian 14, V.V. Antipov et al.15).

Cytogenetic investigations of the marrow and spleen cells of mice undergone flight on ships 2,4 and 5 have made it possible to discover some violations of the division process of the nuclei of these cells. It was shown that under the influence of flight some changes appear in cells' nuclei in the form of chromosome reconstructions and chromosome sticking (M.A. Arsenyeva, V.V. Antipov, V.G. Petrukhin et al.16, M.A. Arsenyeva, V.V. Antipov et al.17). A question naturally arose which of the flight factors caused these changes? The total radiation dose during flight on ship 2 was 10 mrad, and on ships 4 and 5 it did not exceed 2 mrad. Thus it is difficult to suppose that the cytogenetic effect in the marrow and spleen cells was caused by cosmic radiation, even if one admits that the RBE coefficient of the heavy component is 10-20. Further laboratory studies have made it possible to establish that violations of the division processes of cellular nucleus, similar to those which were detected in cells of the marrow and spleen of mice after flight, can appear not only at the action of ionizing radiation, but also under the action of vibrations, accelerations and their combinations. Consequently, one may think that during flight this effect was caused by the action of dynamical factors, and, first of all, vibrations and accelerations (M.A. Arsenyeva, V.V. Antipov et al.17).

Fruit flies (Drosophila melanogaster) of different lines were exposed on ships during all flights. The effect of flight factors, and first of all, cosmic radiation on this object was estimated by the influence of the frequency of the appearance of dominant and sex-coupled recessive lethal mutations, as well as on the frequency of the appearance of primary nondivergence of X-chromosomes.

Analysis of experimental material first of all indicates the absence of distinct dependence of genetic changes in Drosophila melanogaster on flight duration. Considering Ya.L. Glembotsky's data (18) on the influence of space flight factors on the frequency of the appearance of sex-coupled recessive lethal mutations one can see that these statistically confident changes were detected during flights on orbital ships 2 and 4 and Vostok 1. At the same time they were absent during flights of orbital ship 5 and Vostok 2. In experiments with fruit flies the mutagenic effect was absent also during flights of space ships Vostok 3 and Vostok 4. The statistically confident effect was detected from dominant lethals in experiments on ships 2 and 4. In experiments on Vostok 2,3,4 the effect was statistically not confident (G.P. Parfyonov 18). The influence on the frequency of the appearance of primary nondivergence of X-chromosomes was investigated on Vostoks 1,2 and 3. In experiments on Vostoks 1 and 2 the genetic effect was statistically confident, and in an experiment on Vostok 3 it was absent completely (N.P. Dubinin et al.18).

How to explain the appearance of hereditary changes of fruit flies in some flights and the absence of them in other flights? In Ya.L. Glembotsky's opinion, the genetic effect hardly was caused by the action of vibrations and accelerations. If this effect depended on vibrations and accelerations, then their mutagenic action should take place in all seven flights. Hereditary changes in fruit flies apparently are not associated with weightlessness, since in experiments the appearance of the effect did not depend on the increase of time of the action of weightlessness. The authors believe that the leading role in the appearance of genetic effects in fruit flies during flight belongs to the heavy component of galactic rays. It is quite evident that this supposition requires further experimental proofs by laboratory tests elucidating the combined effect of vibrations, accelerations and ionizing radiation on hereditary structures, as well as by flight experiments with great duration of flight.

To estimate the biological effect of cosmic radiation lysogenic bacteria were used which react to the action of relatively small doses of ionizing radiation (0.2 - 0.4 rad) by induced phagoproduction. As was shown by investigations conducted in the USSR under the leadership of Professor N.N. Zhukov-Verezhnikov, the system of lysogenic bacteria, in particular E. coli K-12 (λ), is a very convenient biological model for genetic investigations which permit to record molecular changes, i.e. changes in the state and exchange of bacterial and phagous desoxyribonucleic acid.

Lysogenic bacteria were exposed on orbital ships 4 and 5 and on Vostoks 1,2,3 and 4. Analyzing the experimental material obtained one should note that only in experiments on ships Vostok 3 and Vostok 4 the statistically confident inducing effect of flight factors on lysogenic bacteria E. coli K-12 (λ) was discovered. The inducing effect was more expressed in experiments on space ship Vostok 3 than in experiments on Vostok 4 (N.N. Zhukov-Verezhnikov et al.19).

As pointed out above, the method has made it possible to reveal the inducing effect of ionizing radiation within the limits of 0.2 - 0.4 rad. However, it does not follow from this that discovered induction of lysogenic bacteria in experiments on space ships was associated with the action of only cosmic radiation in small doses. Apparently the detected inducing genetic effect is caused by the complex action of vibrations, accelerations, weightlessness, and ionizing radiation. This supposition is confirmed by laboratory investigations which shows the capability of vibration to increase significantly the sensitivity of lysogenic bacteria to the action of ionizing radiation (N.N. Zhukov-Verezhnikov et al.19).

Dry seeds of higher plants were exposed in all seven ships-satellites. Seeds of wheat and pea are investigated in more detail in a genetic aspect. If we sum up the data on all seeds which flew on space ships and corresponded to the control ones, then statistically confident difference will be revealed between experimental and control materials. This is explained mainly by the fact that due to large quantity of the analyzed material confidence of difference is strongly increased. Analysis of data obtained has shown also that small, but statistically confident increase of the percentage of chromosome reconstructions in cells of roots of embryos of air-dry wheat and pea seeds did not depend on duration of flight (V.V. Khvostova et al.20).

Thus difficulties are quite evident which arouse at the estimate of the rôle of this or that flight factor in the genetic effect in seeds of higher plants. These difficulties are increased by the absence of sufficiently full laboratory data on the influence of vibration and complex effect of ionizing radiation and dynamical flight factors on hereditary structures of seeds. In this connection of some importance is the fact that the mutagenic effect was revealed in barley seeds after balloon flight. This effect was sufficiently well explained by the action of cosmic radiation nuclei (Eugster and Simons 5). Therefore, if we assume that chromosome disturbances in seeds of wheat, pea, pine, beans etc. (see Delone N.L. et al.21, their experiment on Vostok 3) are caused mainly by cosmic radiation, then how can we explain the fact that the mutagenic effect is not increased with the increase of the time of flight, i.e. with the increase of the ionizing radiation dose? It is quite evident that to explain the causes of this interesting phenomenon, further control experiments are needed in laboratories and on space vehicles (for instance, with protective means against different flight factors).

Let us briefly consider the results of biological experiments carried out by A.G. Nikolayev and P.R. Popovich under conditions of space flight. In these experiments the influence of flight factors was investigated, and, first of all, of cosmic radiation and weightlessness on the process of fecundation, the growth and development of the organism, and on the processes of division of cellular nuclei.

Experiments were carried out on Drosophila melanogaster and microspores of Tradescantia paludosa. These experiments have shown the possibility of copulation, egg laying and unnormal development of fruit flies under weightlessness (unpublished data of G.P. Parfyonov et al.). In experiments on Tradescantia microspores the part of the material was fixed by P.R. Popovich after 56 hours after launching which excluded the influence of vibrations and accelerations acting on the object during the ship's descent. As a result of an analysis of the material received a new type of reconstructions has been revealed - spherical fragments which were recorded not only in the metaphase, anaphase and telophase, but also in the prophase and interphase. Besides, different disturbances of mitosis have been observed, for instance, nondivergence of chromosome complexes, etc. (N.L. Delone et al.22). The results of the flight experiment with Tradescantia microspores carried out by Cosmonaut V.F. Bykovsky should help find the causes of these changes. He managed to fix the experimental material three times during flight, and thus the opportunity is offered to differentiate the action of vibrations and accelerations appearing at the ship's ascent and descent due to the influence of weightlessness and cosmic radiation. The treatment of the material obtained is not yet completed. However, preliminary results give grounds to believe that the aims set in the experiment will be fulfilled in a full volume.

Of great interest are the experiments carried out on the American satellite Discoverer XVII. The satellite carried cultures of tissues of man's organism - cells of synovial membrane of the joint and cells of the eye's conjunctiva, different human and animal blood preparations as well as bacterial spores stable to temperature and algae culture. As is known, the flight of this satellite coincided with a very intensive solar flare. The biological objects under test were subjected to irradiation by the total dose of 30-35 rad. However, during laboratory studies made on these objects no effect of cosmic radiation was detected except for bacterial spores. It is evident that, unfortunately, the investigation methods used turned to be insufficiently sensitive (E. Bulban 23).

From the not complete list of papers cited in the present report it is evident that extensive work has been done by Soviet and American scientists on selecting objects and developing adequate tests for studies of the biological effect of cosmic radiation. The extensive experimental material obtained in flight experiments on aerostats, high-altitude and ballistic rockets, ships-satellites may be essentially regarded as background data for further radiobiological investigations in the cosmos. Rapid successes in the development of rocketry give grounds to believe that opportunities for conducting such investigations will be extended in the near future.

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PROBLEMS OF RADIATION SAFETY OF SPACE FLIGHTS

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ABSTRACT

The main problems of radiation safety of space flights are discussed:

investigation of physical parameters of cosmic radiation - the spectrum of components and their energies, determination of ionizing radiation in space and in time, etc.;

determination of relative biological effectiveness of individual components of cosmic radiations;

elucidation of specific contribution of cosmic radiation to the biological effect of space flight factors;

investigation of the effect of cosmic radiation on heredity and variability of organisms;

determination of admissible limit radiation doses for space flights;

development of methods of dosimetry of ionizing radiations aboard space vehicles;

development of effective means of physical and pharmacochemical protection of organisms against radiations;

prediction of radiation situation in outer space; selection of orbits least dangerous in radiation aspect.

Biological experiments conducted on different space vehicles, astrophysical investigations of outer space, and, at last, flights of Soviet and American astronauts have convincingly demonstrated radiation safety of short-time orbital flights below the Earth's radiation belts and in the absence of enhanced solar activity. Radiation doses received by cosmonauts are small and cannot exert harmful influence on man's organism.

However, at more prolonged flights with the crossing of the radiation belts, and especially during solar flares, ionizing radiation can become a real threat to human health and life.

Consequently, today the problems of ensuring radiation safety of space flights are not only of theoretical interest but also of practical importance. Let us briefly discuss the main problems. This is, first of all, the study of relative biological effectiveness (RBE) of protons and heavy nuclei of different energies, the investigation of the combined action of these particles (together with other flight factors) on the organism, and the development of effective physical, biological and pharmacological protective agents.

It is quite evident that successful study of the biological effect of cosmic radiation and development of effective protective measures are inconceivable without maximally full information about physical characteristics of cosmic radiation: the composition, energy spectrum of individual components, density and spacial distribution. Alongside the acquisition of data on the physics of cosmic radiation the investigation should be made of biophysical peculiarities of the action of the heavy component.

The solution of the above mentioned tasks is closely associated with the successful development of the methods of physical and biological dosimetry of ionizing radiations which in the system of measures ensuring radiation safety of space flights occupies the prominent place. Due to imperfection of methods of physical dosimetry of high-energy particles, especially on the present stage of research it is rational to check physical measurements carried out during flights by biological reactions using for these purposes the most investigated radiobiological objects.

Let us briefly discuss the problem of relative biological effectiveness of individual components of cosmic radiation, and, first of all, protons - the predominant type of penetrating radiations in outer space.

At present the biological effect of high-energy protons, their RBE, as compared to X-rays and gamma rays, are investigated mainly in laboratory conditions at different accelerating installations. Experiments were conducted on different biological objects: monkeys (Zellmer and Allen 1961), dogs (A. Lebedinsky, Yu. Nefedov, N. Ryzhov et al. 1962), rats, mice (E. Kurlandskaya et al. 1959, 1961, 1962, G. Avrunina et al. 1961, V. Fyodorova and G. Avrunina 1959, V. Antipov, B. Razgovorov, V. Shashkov et al. 1962), fruit flies (Ya. Glembotsky et al. 1962, G. Parfyonov et al. 1962), dry seeds of higher plants (V. Khvostova et al. 1962, L. Gordon et al. 1962).

The most complete data are obtained in experiments on mice and rats. In these experiments RBE was estimated according to survival rate, and change of the blood production system. Comparative investigations were made of cancerigenic effect of protons and X-rays (E. Kurlandskaya et al. 1962, M. Raushenbakh, V. Antipov, B. Davydov et al. 1963).

Analyzing data in literature and results of our own investigations we can conclude that RBE of protons with energies of 120-660 Mev does not exceed 1 for rats, mice, fruit flies, seeds of higher plants. For monkeys (Zellmer et al.) and dogs (A. Lebedinsky et al.) RBE of protons with energies of 730 and 550 Mev lies within the limits 1-2. It should be stressed that the above mentioned experiments, especially on monkeys and dogs, are not numerous. Therefore, they require repetition and more precise character of experimentation under identical irradiation conditions with the use of the same estimation tests. Of great interest will be further studies of remote consequences of irradiation - the cancerigenic and leukemic effects of protons as well as studies of the biological effect of protons with energies less than 100 Mev whose RBE according to calculations, should be higher than that of protons with energies of 120-660 Mev.

Estimating RBE of high-energy protons obtained at different accelerating installations one should take into account the impulse character of irradiation and large dose rates. These factors should certainly affect results of the biological effect of radiation, and, therefore, they should be taken into account at tentative determination of RBE of protons of primary cosmic radiation, the inner radiation belt and solar flares. Unfortunately up till present time it was impossible to conduct flight experiments for estimating satisfactorily relative biological effectiveness of protons of outer space.

Still less experimental data are available on biological effectiveness of alpha-particles (helium nuclei) and nuclei of more heavy elements. On the basis of calculations, RBE of these particles are taken to be equal 2-10, and, according to some tests, more than 10. Further studies of RBE of heavy particles are closely connected with development of engineering of nuclear research, with creation of more powerful accelerating installations as well as with extension of radiobiological research in outer space.

The problem of investigating the complex influence of ionizing radiation and other flight factors (vibration, acceleration, weightlessness, changed gaseous composition, etc.) on the organism is also very urgent.

Experimental data on this problem are almost absent. However, it is very important to know what is the specific contribution of cosmic radiation to the general action of flight factors on the human organism. It is also very important to know what is the influence of other flight factors on qualitative and quantitative aspects of the biological radiation effect. Without these data it is impossible to give scientifically substantiated recommendations on pharmacotherapy and prophylaxis of radiation injuries.

Our investigations (V. Antipov, B. Davydov, V. Vysotsky 1962, T. Lvova and N. Suprunenko 1961, 1962, 1963, etc.) indicate that acceleration and vibration exert different influence on the development of radiation injuries which depends on the succession of the application of these factors. For instance, the effect of vibration and acceleration on the fifth-seventh day after irradiation aggravate the development of radiation sickness (reaction). If, however, vibration and acceleration are used before irradiation, they do not aggravate the radiation effect. Moreover, they even lessen it slightly.

The absence of sufficient experimental data on RBE and on combined action of flight factors and radiation prevent us from giving scientifically substantiated recommendations on permissible limit radiation levels for astronauts.

The limit permissible dose of cosmic radiation for cosmonauts (25 rem) for flight of duration from several days to one year, which we recommend, is based on calculated physical data with the account of radiobiological experimental and clinical facts about the injuiring effect of ionizing radiation under terrestrial conditions. Apparently transfer of these data to cosmic radiation is inadmissible without reservations. Therefore, the recommendation on permissible dose of 25 rem should be regarded as temporary. With the acquisition of experimental data on the biological effect of individual components of cosmic radiation, on the effectiveness of radioprotective compounds this dose will be altered.

Of great practical and theoretical interest is the problem of finding effective radioprotective pharmacochemical compounds. Their use will permit to decrease the weight of physical protection, thus decreasing the weight of a flying vehicle and increasing the time of flight.

By the efforts of many scientists working in this sphere, preparations are discovered, and synthecized capable of protecting the organism against lethal doses of ionizing radiation. However, the majority of these preparations may be hardly used under specific conditions of space flight.

We believe that pharmacological preparations designed as individual protective means of the crew against the injuring effect of cosmic radiation should meet the following main requirements: They should have high effectiveness combined with nontoxicity, they should not exert any additional action during repeated long-time use, they should not cause even short-time loss of working capacity (performance), they should not exert negative influence on resistance of the organism to the action of different flight factors-overloads, psychic stress, weightlessness, etc.

One should take into account that apparently pharmaco-chemical means of protection against radiation should be used not only for cosmonauts, but also for the whole bio-complex of a space ship.

We have treated only some radiobiological problems which, in our mind, are not only of theoretical, but also of great practical importance in the solution of the problem of the protection of the cosmonaut from the injuring effect of cosmic radiation. Of exceptional interest is also the study on problems of the genetic effect of cosmic radiation, of the biological effect of the heavy component, etc. These problems deserve special discussion. However, it should be noted that Soviet geneticists have accumulated extensive material on the action of different space flight factors on the genetic apparatus of various biological objects. (N.N. Zhukov-Verezhnikov et al. 1960, 1961, 1962, N.P. Dubinin et al. 1960, 1961, 1962, M.A. Arsenyeva et al. 1961, 1962, Ya.L. Glembotsky et al. 1961, 1962, G.P. Parfyonov, 1961, V.V. Khvostova et al., N.L. Delone et al. 1962, N.I. Nuzhdin et al. 1963).

The solution of the above mentioned problems will make it possible to work out a scientifically substantiated system of measures guaranteeing radiation safety of space flights. One of the possible schemes of this system partly checked during flights of Soviet space pilots envisages:

the selection of orbits not dangerous in radiation respect;

the prediction of radiation situation in outer space, especially solar flares;

reliable dosimetric control of radiation levels in the cabin of a space ship;

effective physical, pharmaco-chemical and biological means protecting astronauts from the injuring effect of cosmic radiation.

Thus the consideration of some principal radiobiological problems has shown that in this shpere there are very many unsolved questions. This is understandable since space radiobiology is a very young branch of young science - space biology. However, there are grounds to believe that combined efforts of scientists of different specialities, representatives of different countries of the world, will lead to a successful solution of the problem of radiation safety of space flights in near outer space.

THE ENSURING OF RADIATION SAFETY DURING FLIGHTS OF SOVIET COSMONAUTS Yu.A. GAGARIN, G.S. TITOV, A.G. NIKOLAYEV AND P.R. POPOVICH

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ABSTRACT

A system of radiation safety measures during manned space flights provided prediction of radiation situation in outer space, measurements of the integral dose and dose rate directly on a ship-satellite, biological dosimetry of cosmic radiation as well as use of pharmaco-chemical antiradiation agents in case of emergency. The results obtained have made it possible to estimate positively the radiation safety system of manned space flight.

During flight along the orbit of the ship Vostok a space pilot is subjected to the action of primary cosmic radiation (galactic rays) and Bremsstrahlung produced at the interaction of the outer radiation belt electrons with the ship's hull. The possibility is not also excluded of small irradiation by protons of the inner radiation belt which, for instance, in the region of the Brazilian magnetic anomaly descends to heights of 230-320 km.

According to S.N. Vernov et al. (1), V.E. Nesterov et al. (2), at altitudes of 180-340 km at the orbital inclination of 65°, approximately 90 per cent of the absorbed dose is due to primary cosmic radiation, and 10 per cent is due to radiation of the Earth's radiation belts. It should be noted that strongly ionizing heavy nuclei, which, as protons, can cause nuclear disintegration stars in the biological object, constitute the part of primary cosmic radiation. Taking into account biological peculiarities of the action of the heavy component, one should expect that biological effectiveness of radiation of this type will be much higher than the effectiveness of X-rays and gamma rays.

Measurements carried out aboard spaceships-satellites II-V and ships Vostok have shown that at these heights the integral 24-hour radiation dose varies within 8-15 millirads. It is quite evident that even high biological effectiveness for the heavy component of primary cosmic radiation is taken into account, the radiation dose received during short-time flights at heights of 180-250 km is not dangerous.

At these heights protons produced during solar flares constitute a real threat for the cosmonaut's health. Solar protons have energy from several Mev to 700 Mev, and in some cases their energy can reach several Bev.

After mighty solar flares the intensity of cosmic rays at large distances from the Earth beyond the magnetic field is increased by thousands and even tens of thousands times. This leads to an enormous increase of doses up to lethally dangerous levels on the order of 500 rad. In orbits of ships of the Vostok type where the shielding effect of the Earth's magnetic field is felt, the irradiation dose decreases reaching several tens of rads per flare. Taking into account that protons of solar flares act in a complex or against the background of other flight factors increasing radiation, reaction, there are grounds to suppose that under these conditions the dose of several tens of rad will be dangerous for the cosmonaut's health.

Production of solar flares occurs without any definitely expressed regularity in time. Therefore, the probability of getting into a flare of different intensity depends on average probability of its appearance and on duration of flight.

Besides protons of solar flares, ionizing radiation caused by the American high-altitude explosion over Johnson Island in the Pacific Ocean on July 8, 1962, constituted a grave danger for space pilots A.G. Nikolayev and P.R. Popovich. Taking into account the above mentioned, the system of measures guaranteeing radiation safety during flights of ships Vostok provided for

prediction of radiation situation in outer space;

measurement of the integral dose and the dose rate directly on a ship-satellite;

biological dosimetry of cosmic radiation;

use of pharmaco-chemical antiradiation agents under conditions of emergency.

To predict radiation situation in outer space the "solar service" was established to observe the state of solar activity. This service functioned before and during flight. Astrophysical observatories and heliophysical stations situated at different points of the Soviet Union conducted continuous optical, magnetic and radio observations of the Sun. Besides, in the upper atmosphere direct measurements of the intensity of radiations were carried out by means of the instrumentation lifted on balloons. Balloon flights were accomplished six-seven times during 24 hours in different places of the USSR, including polar regions. Information obtained about radiation situation in outer space enabled the organizers of flight to take decisions on the accomplishment of flight and its successive program.

To increase radiation safety the ships had the necessary design shield which protected the cabin against penetration of some part of cosmic radiation, and which, to a considerable degree, protected the cabin against the effect of radiation associated with the nuclear explosion in outer space.

The astronauts were provided by special radioprotective compounds for the case of sharp deterioration of radiation situation for prophylaxis of the injuring effect of radiation.

Dosimetric control on ships Vostok 1 and Vostok 2 was carried out by means of individual dosimeters ILK, IFK and thermoluminescent glasses. The total dose for flight was less than 1 mrad in Y.A. Gagarin's flight and 12 mrad in G.S. Titov's flight.

In connection with the increase of flight time of ships Vostok 3 and Vostok 4, special on-board dosimetric instrumentation was installed whose telemetry readings were transmitted to ground observation points. Besides, the set of individual dosimeters was extended. Apart from dosimeters with which Yu.A. Gagarin and G.S. Titov were provided, A.G. Nikolayev and P.R. Popovich had DKP-50, nuclear photo-emulsions, etc.

According to data of on-board dosimeters, the total dose during the Vostok 3 flight was 43 ± 1 mrad, and during the Vostok 4 flight it was 32 ± 1 mrad (S.N. Vernov, I.A. Savenko et al. 3).

Readings of individual dosimeters DKP-50 did not go out of the limits of errors caused by self-discharge.

According to data obtained by means of individual dosimeters placed on cosmonauts, the absorbed dose was from 48 to 64 mrad for A.G. Nikolayev, and from 37 to 46 mrad for P.R. Popovich (see I.B. Kerim-Markus et al. 4).

The set of ionizing radiation detectors situated in the bioblock has made it possible to estimate radiation conditions in which biological experiments were conducted.

According to the data of the study of nuclear photoemulsions and scintillation dosimeters, the integral dose in places of location of bioblocks on the ship Vostok 3 was 56 ± 8 mrad, and on Vostok 4 it was 45 ± 7 mrad during flight. The contribution of charged particles to the integral dose was about 40 per cent, and approximately two thirds of this contribution fell to heavy nuclei ($Z > 1$). According to the data of dosimeters IFK and ILK, during flight the total dose was about 50-60 mrad (V.N. Lebedev, V.S. Morozov et al. 5).

Thus the average dose rate of radiation during flights of space ships Vostok 3 and Vostok 4 was 13 ± 2 mrad per 24 hours, i.e. noticeably exceeded the dose rate observed on Vostok 1 (7.2 mrad/24 hours) and on Vostok 2 (8.4 mrad/24 hours). The increase of the dose rate may be accounted for by possible residual radiation caused by the high-altitude nuclear explosion on July 8, 1962.

As evident from the above cited results of measurements, integral doses obtained by different methods agree with each other within the measuring errors. As is well-known, these doses do not exceed the norm established for persons working with penetrating radiation sources, and are not dangerous for human health.

Alongside the above mentioned instrumentation, different biological objects were carried aboard spaceships: air-dry seeds of plants (wheat, pea, onion, pine, cabbage, carrot, etc.), microspores of Tradescantia paludosa, lysogenic culture of E. coli K-12 (λ), Drosophila melanogaster, human cancer cells, eggs of swine's Ascaris. These objects were used for biological dosimetry of cosmic radiation, and for investigation of the injuring effect of flight factors, including ionizing radiation, on hereditary structures and physiological functions of a cell, of an organism.

It should be noted that results of radiobiological investigations agree quite satisfactory with the data of physical measurements. These experiments have shown that injuring effect of flight factors on hereditary structures of some objects may be revealed by means of genetic tests. For instance, different disturbances of mitosis were observed in sprouts of wheat (V.V. Khvostova et al. 6), in microspores of Tradescantia (N.L. Delone et al. 7), an inducing effect is detected in lysogenic bacteria, (N.N. Zhukov-Verezhnikov et al. 8). It should be emphasized that these effects are not great in a quantitative respect. At the same time the use of physiological methods of research has not permitted to reveal any expressed changes typical of radiation injury in life functions of different objects.

The revealed genetic changes probably are caused by the effect of a totality of flight factors, including ionizing radiation in small doses. The possibility is not excluded that such factors, as vibration, accelerations etc., are sensitizers for some objects, as far as the effect of cosmic radiation is concerned. In our opinion, the supposition that the above mentioned injuries of hereditary structures are specific and are caused by the heavy component of galactic rays is less substantiated. It is quite evident that the causes and mechanism of genetic disturbances observed in some biological objects under the influence of flight factors require further investigations.

General clinical observations and special laboratory examinations of Yu.A. Gagarin, G.S. Titov, A.G. Nikolayev and P.R. Popovich regularly conducted after completion of flight also confirm convincingly that during these flights there was no negative effect of cosmic radiation on space pilots' health.

Thus, the results obtained permit to estimate positively the system of measures used to guarantee radiation safety during manned space flights on board ships of the Vostok type.

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ON THE BIOLOGICAL EFFECT OF HIGH-ENERGY PROTONS

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ABSTRACT

Results are discussed of the investigation into the injuring effect of protons with energies 660 and 120 Mev aimed at determination of relative biological effectiveness (RBE) of these particles and of the investigation on mice into radioprotective properties of cystamine, serotonin, etc. under conditions of irradiation by protons. Experiments were carried out on different biological objects (rats, mice, fruit flies etc.) with the use of different technique of investigations.

The experiments have shown that RBE of protons with energies 660 and 120 Mev for LD_{50} was 0.7 for mice and rats. The same results were obtained during relative estimates of chromosome disturbances in cells of the marrow of mice, in spronts of seeds of higher plants, during determination of recessive sex-coupled and dominant lethal mutations of Drosophila melanogaster.

The effectiveness is shown of some pharmaco-chemical substances (cystamine, serotonin, etc.) used as protective agents under conditions of the effect of high-energy protons.

In the era of the conquest of outer space by man the problem of the biological effect of cosmic radiations on living organisms is not only of a theoretical, but also of great practical importance.

Cosmic radiation, especially during long-time flights beyond the Earth's magnetic field, will be one of the main obstacles on the path of the conquest of interplanetary space (1,2). From a practical point of view, in the aspect of radiation danger, of special interest are corpuscular radiations high-energy protons and heavy multiply charged nuclei.

It is assumed that if we have satisfactory information about physical characteristics of cosmic radiation, the absence of sufficient data on Relative Biological Effectiveness (RBE) of individual components of cosmic radiation is the main obstacle for establishing scientifically substantiated permissible radiation levels and developing effective protective measures.

RBE of different types of radiations, corpuscular radiations included, depends on many factors. Ionization density and linear energy losses during the passage of radiations through matter play great role in this respect. It is known that the increase of specific ionization from 3 to 100 ion pairs per 1 micron of the path affects little RBE which remains approximately equal to unity. The increase of ionization density from 100 to 1000 ion pairs per 1 micron gives the RBE increase proportionally to the specific ionization logarithm (3). It should be emphasized that at the estimate of RBE, alongside physical peculiarities of the action of radiations, one should also take into account biological peculiarities, the level of organization and the functional state of a cell, organ, system or an integral organism, as well as the character of tests by means of which the relative effectiveness of different types of radiations is determined.

Protons are known to be the most widely spread kind of penetrating radiation in outer space. They constitute 85 per cent of primary cosmic radiation (galactic rays), they are generated in large quantities during solar flares, and are the part of radiation of inner and outer radiation belts.

At present only first steps are taken in the determination of RBE of protons. According to data by E.B. Kurlandskaya et al. (4) and G.A. Avrunina (5), biological effectiveness of protons turned to be not higher, and for some indices (mortality rate, variation of morphological composition of peripheric blood) even lower than biological effectiveness of X-rays. For instance, RBE for LD_{50} is 0.55 for mice and 0.65 for rats, respectively. A.V. Lebedinsky, Yu.G. Nefedov, N.I. Ryzhov et al. (6) have found that the RBE coefficient of protons with the energy 510 Mev is 0.8 for rats and 1.2 for dogs.

According to R.W. Zellmer and R.G. Allen (7), the RBE coefficient for protons with the energy 730 Mev, as compared to gamma rays, amounts to approximately 2. This conclusion is made by them on the basis of experiments with monkeys in which RBE was estimated from time of appearance, the graveness of the process of development of iridocyclite, erythemas and other injuries of sight's organs. According to P. Bonet-Maury, A. Deysine et al. (8), RBE for protons with the energy of 157 Mev for LD_{50} for rats amounts to 0.77 ± 0.1, as compared to X-rays.

In this report we present results of experiments for studies of RBE of protons with the energy 660 and 120 Mev whose specific ionization is 6 and 20 ion pairs per micron, respectively (G.F. Murin, V.S. Morozov et al.). The experiments were conducted on various biological objects with the use of different methods of investigation. The objects were irradiated in a pulsed proton beam of the synchrocyclotron of the Joint Institute for Nuclear Research at Dubna with the current density of 10^8 - 10^9 particles per square cm per sec. The number of pulses was about 100 per 1 sec. with the duration of 200-400 msec each. In our experiments the dose rate determined from induced activity in carbon plates was 400-700 rad/min for E=660 Mev and 80-120 rad/min at

E=120 Mev. The RBE of protons, as compared to gamma rays, was estimated by means of different tests characterizing life functions and heredity of a cell, of an organism.

The experiments conducted have shown that RBE for protons with energies 660 and 120 Mev for LD_{50} for mice and rats was about 0.7. Clinical examination of animals have also shown somewhat lower effectiveness of protons as compared to gamma rays (V.S. Shashkov, B.L. Razgovorov, V.V. Antipov et al.). The same results were obtained during comparative evaluation of chromosome breaks in the cells of the mice marrow (M.A. Arsenyeva, L.A. Belyayeva et al.), in sprouts of seeds of higher plants-wheat, pea, barley and others (V.V. Khvostova et al., L.K. Gordon), at the determination of recessive sex-coupled and dominant lethal mutations of Drosophila melanogaster (Ya. L. Glembotsky, G.P. Parfyonov et al.).

It should be emphasized that at the estimate of RBE of high-energy protons obtained at different acceleration devices it is necessary to take into account the impulse character of irradiation and large dose rates. These factors affect the results of the biological action of radiation, and, therefore, they should be taken into account at tentative determination of RBE of protons of primary cosmic radiation, the inner radiation belt and solar flares.

For a more complete estimate of the protons' RBE, of great interest are the results of experiments aimed at investigation of radioprotective properties of various pharmaco-chemical agents used under conditions of irradiation by protons. It is quite evident that such investigations are also necessary for the solution of the principle question-on the possibility of the use of pharmaco-chemical protectors at the action of corpuscular radiations.

By the present time an extensive experimental material has been acquired which shows the effectiveness of a number of pharmaco-chemical preparations used as protective agents under conditions of the effect of X-rays and gamma rays.

Thus analyzing data in literature and results of the authors' own investigations we first of all come to the conclusion that RBE of protons with the energy from 660 to 120 Mev determined in experiments on mice and rats, fruit flies, seeds and other biological objects does not exceed 1. These facts quite satisfactorily confirm the supposition expressed by us that for the above mentioned values of specific ionization (6-20 ion pairs per micron of tissue) RBE should not exceed 1.RBE exceeding 1 was detected for protons of 510 Mev in experiments on dogs (6) and for protons of 730 Mev in experiments on monkeys (7). Evidently this difference to some extent is due to the type of an animal and depends on the tests by which RBE was estimated.

The results obtained give grounds to believe that there is the perspective of using some preparations as protective devices for space pilots and the entire biocomplex against harmful effect of high-energy protons.

Of great theoretical and practical interest for space biology and medicine will be extensive investigations of RBE of protons with the energy of 100 Mev as well as the test of the effectiveness of pharmaco-chemical antiradiation agents under these conditions.

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