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# THE EFFECTIVENESS OF THE USE OF AN AERODYNAMIC LIFT WITH DESCENT IN THE ATMOSPHERE OF MARS

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Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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## U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

| Block | Italic | Transliteration | Block | Italic | Transliteration |
|---|---|---|---|---|---|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

## GREEK ALPHABET

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Alpha | Α | α | α | Nu | Ν | ν | |
| Beta | Β | β | | Xi | Ξ | ξ | |
| Gamma | Γ | γ | | Omicron | Ο | ο | |
| Delta | Δ | δ | | Pi | Π | π | |
| Epsilon | Ε | ε | ϵ | Rho | Ρ | ρ | ϱ |
| Zeta | Ζ | ζ | | Sigma | Σ | σ | ς |
| Eta | Η | η | | Tau | Τ | τ | |
| Theta | Θ | θ | ϑ | Upsilon | Υ | υ | |
| Iota | Ι | ι | | Phi | Φ | φ | ϕ |
| Kappa | Κ | ϰ | κ ϰ | Chi | Χ | χ | |
| Lambda | Λ | λ | | Psi | Ψ | ψ | |
| Mu | Μ | μ | | Omega | Ω | ω | |

## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

| Russian | English |
|---|---|
| sin | sin |
| cos | cos |
| tg | tan |
| ctg | cot |
| sec | sec |
| cosec | csc |
| sh | sinh |
| ch | cosh |
| th | tanh |
| cth | coth |
| sch | sech |
| csch | csch |
| arc sin | $\sin^{-1}$ |
| arc cos | $\cos^{-1}$ |
| arc tg | $\tan^{-1}$ |
| arc ctg | $\cot^{-1}$ |
| arc sec | $\sec^{-1}$ |
| arc cosec | $\csc^{-1}$ |
| arc sh | $\sinh^{-1}$ |
| arc ch | $\cosh^{-1}$ |
| arc th | $\tanh^{-1}$ |
| arc cth | $\coth^{-1}$ |
| arc sch | $\mathrm{sech}^{-1}$ |
| arc csch | $\mathrm{csch}^{-1}$ |

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| | |
|---|---|
| rot | curl |
| lg | log |

## GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

AF/ST-75-0331.

AUTHORS cont.

N. M. Ivanov,
A. I. Martynov.

The effectiveness of the use of an aerodynamic lift with descent in the atmosphere of Mars.

Are examined two limiting cases of a reduction in the descent vehicle, which possesses lift aerodynamic force, in the atmosphere of Mars - the quite simple in realization descent with constant lift-drag ratio and descent most complex in realization with the optimum control of lift, that makes it possible to obtain the minimum final velocity for an apparatus with these characteristics. In the magnitude of a difference in the final velocities when using these two views of descent it is defined, to which of them it is possible to give preference in each concrete case. Are given numerical results.

The solution to the problem of the aerodynamic descent of apparatuses to the surface of Mars is hinder/hampered on the strength of the fact that the atmosphere of the planet is extremely is rarefied. By force this use of ballistic type apparatuses conjugate/combined with the greatest difficulties, so as magnitude of the given load on frontal surface in such descent vehicles (DV) must not exceed ~70 kgf/m² [1, 2]. The introduction of lift makes it possible substantially to facilitate accomplishing of the objective of the aerodynamic descent:

to decrease the final velocity of $V_K$- velocity to the moment of the connection of the system of soft landing, to increase load on the frontal surface DV and, etc.

The effectiveness of the use of an aerodynamic lift for the descent of space vehicle (KA) in the atmosphere of Mars can be defined by the magnitude of the final rate to which was inhibited the vehicle, since for active braking with the help of the propulsion system of each 10 m/s of a velocity increment of $V_K$ is spent several dozen kilograms of fuel load and the structural elements of the system of soft landing.

In the present work are examined two limiting cases of a reduction DV, which possesses lift aerodynamic force - the quite simple in realization descent with constant lift-drag ratio (K=const) and the most complex in realization descent with the optimum control of lift (K=var), that makes it possible to obtain the minimum final rate for DV with the assigned characteristics.

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In the magnitude of a difference in the final rates $\delta V_K = (V_K)_{K=const} - (V_K)_{K=var}$, which are achieved when using these

two views of descent under other identical conditions, it is possible to judge to which of them it is necessary to give preference in each concrete case.

We will examine case of the entrance KA into the atmosphere of Mars from the trajectory of direct/straight flight/passage ground-Mars, for which the rate

the atmospheric entry of Mars $V_{BX} \approx 6$ km/s. On the trajectory of descent is superimposed the constraint by height of the mission KA above

the surface of the planet:

(1).

$$H \geqslant (H_{min})_{доп}$$

During the simulation of the equations of motion of the center of mass DV was utilized "operational" model of the atmosphere of Mars [1, 2].

Descent with constant lift-drag ratio. We will examine traffic DV within operational reentry corridor.

The lower boundary of operational reentry corridor is defined by the minimum altitude of the conditional pericenter of the trajectories of entrance $d_{\pi}^{H}$ at which is still possible the execution of constraint (1), if $K=K_{max}$. The upper bound is defined from the condition of capture DV by the atmosphere of Mars. In this case the vehicle is considered seized by the atmosphere, if the maximum altitude of mission after the first insertion into dense layers of the atmosphere does not exceed 100 km.

It should be noted that the lower boundary of operational reentry corridor substantially depends on the designed-ballistic parameters DV [given load on its frontal surface of $P_x=G/c_x S$, where $c_x$, S and G are a drag coefficient, the area of midsection and weight (on ground) DV, and the lift-drag ratio DV $K_6=c_y/h$ at balance angle $\alpha_6 = const$] and from the minimally permissible altitude $(H_{min})_{dop}$. The altitude of the conditional pericenter $H_\pi^u$ being grow/risten with the increase $P_x$ and $(H_{min})_{ion}$ also, during decrease in $K_6$. Thus, for instance, increase $P_x$ from 200 to 650 kgf/m² leads to increase H from -270 to -100 km, an increase $(H_{min})_{ion}$ with 3 to 9 km leads to increase $H_\pi^u$ from -230 to -130 km, and decrease $K_6$ from 0.5 down to 0.3 changes $H_\pi^u$ from -287 to -113 km (Fig. 1).

***********EDITOR: PLEASE CHECK FOR ALL CYRILLIC OR UNCLEAR ITEMS ON THE TABLE (FIGURE) WHICH MAY HAVE BEEN LEFT OUT***********

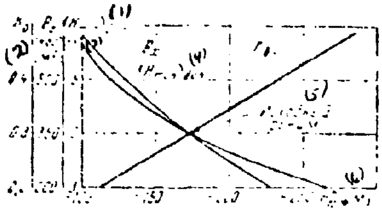


Fig. 1.

Key: (1) dopa. (2) kgf/m². (3) km. (4) dopa. (5) the initial process/conditions. (6) km.

Fig. 2 gives the dependences of the magnitude of the final rate from the designed-ballistic parameters DV ($P_x$ and $K_б$) and from the altitude of the conditional pericenter of the trajectories of entrance. It is evident that with descent with $K_б$ = const the magnitude of the final rate substantially depends on the altitude of the conditional pericenter of the trajectory of entrance, achieving maximum near the middle of reentry corridor.

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Thus, for instance, for DV with $P_x$=350 kgf/m² and $K_б$=0.3 ($V_{0x}$=6 km/s

$$V_к = 630 \text{ m/s with } H_п = H_п^н = -170 \text{ km},$$
$$V_к = 740 \text{ m/s with } H_п = H_п^в = -50 \text{ km},$$
$$V_к = 760 \text{ m/s with } H_п = -80 \text{ km}.$$

m/s; with; km.

Let us note also that the minimum value of the final rate in the case of traffic DV with the constant lift-drag ratio is achieved during traffic along the lower boundary of operational reentry corridor. In this case the maximum spread in the magnitude of the final rate during traffic within operational reentry corridor with $K_б$=const is 120-150 m/s. As one would expect, an increase in the load on frontal surface and lift-drag ratios leads to an increase in the final rate. So, for example during increase $P_x$ from 200 to 650 kgf/m² $V_к$ grow/rises from 650 to 976 m/s, and during change $K_б$ from 0.3 to 0.5 the value of $V_к$ increases from 700 to 1016 m/s (are examined the maximum values $V_к$ within the operational corridor entrance).

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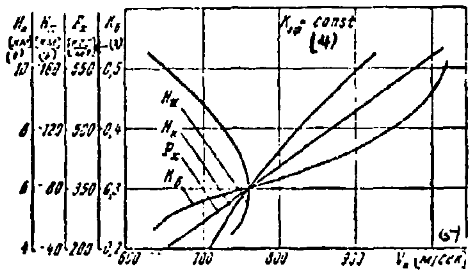

Fig. 2.

Key: (1) km. (2) km. (3) kgf/m². (4) ef. (5) m/s.

Optimum control of the final rate. For determining the optimum law of control of the "effective" quality $K_{эф}=K_{0}\cos\gamma$ ($\gamma$ is an angle of the bank DV) from the condition of the minimum of the final rate of descent was solved the corresponding variational problem.

Was examined the plane motion of the center of mass DV in the atmosphere of being unrotated Mars:

$$\left.\begin{aligned}\dot V&=-\frac{\rho V^2 g_3}{2P_x}-g_M(H)\sin\theta;\\ \dot\theta&=K_{эф}\frac{\rho V g_3}{2P_x}-g_M(H)\frac{\cos\theta}{V}+\frac{V\cos\theta}{R+H};\\ \dot H&=V\sin\theta.\end{aligned}\right|$$

(2).

Here V, H - velocity and flight altitude; $\theta$ - the angle of the path inclination DV toward the local horizon; R - the mean radius Mars; $\rho$ - the atmospheric density of Mars; $g_M(H)$ - the acceleration of gravity on Mars; $g_3$ - the acceleration of gravity on ground; point designated time derivatives t.

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The value of the given load on the frontal surface DV $P_x$ was received as constant in an entire trajectory of descent.

The objective was accomplished during the constraints

$$H_k - H(t) \leq 0; \quad (3)$$

$$-K_6 \leq K_{\text{эф}} \leq K_6 \quad (4)$$

and under the boundary conditions

$$\left.\begin{array}{l} V(t_0)=V_{вх};\quad \theta(t_0)=\theta_{вх};\quad H(t_0)=H_{вх};\quad H(t_к)=H_к; \\ t_к - \text{it is free} \end{array}\right\} \quad (5)$$

Index "0" designated the initial conditions, which correspond to the entrance KA into the atmosphere of Mars.

For the notation of the necessary conditions of optimum character was utilized the principle of L. S. Pontriagin's maximum [3, 4].

The carried out investigation showed that the optimum control depending on the parameters DV $P_x$ and $K_6$ and minimally the permissible flight altitude $(H_{min})_{доп}$ at the identical conditions of entrance can be two types.

First type optimum trajectory maintains the phase of traffic along constraint (3). During izovysotnom phase of trajectory the control is lefined unambiguously from the condition of the passage of extremal along constraint [4] and takes the form

$$K_{эф}=\left(\frac{1}{\bar{V}^2}-1\right)\frac{2P_x}{g_м \rho_к (R+H_к)}, \quad \text{where} \quad \bar{V}=\frac{V}{\sqrt{g_м(R+H_к)}}.$$

Descent from constraint is implemented inside the permissible region of phase coordinates with the magnitude of the effective quality $K_{эф}=+K_б$,

which remains constant to the end of the trajectory. It should be noted that in the presence of horizontal phase in the composition of the optimum trajectory of the entrance functional of $V_к$ does not depend on the initial conditions $V_0$, $\theta_0$ and $H_0$.

Second type optimum trajectory does not maintain izovysotnogo phase. The program of control is the program with the one-time changeover of effective quality with $K_{эф}=-K_б$ [redacted] on $K_{эф}=+K_б$.

It is necessary to note that a decrease in the minimally permissible flight altitude DV above the surface of Mars, and also load on the frontal surface DV and the magnitudes of lift-drag ratio leads to a decrease in the time interval, within which DV moves over constraint $H=(H_{min})_{доп}$. Moreover for some types DV there is an altitude $(H_{min})_{кр}$ [redacted] at which during fulfillment of the conditions $(H_{min})_{доп} < (H_{min})_{кр}$ [redacted] the optimum trajectory does not maintain izovysotnogo phase. Thus, for instance, for DV with $P_\gamma$=250 kgf/m² and $K_6$ =0.3 magnitude $(H_{min})_{upex}$ =2.75 km, but for DV with $P_\gamma$=80 kgf/m² and $K_6$=0.4 this magnitude is equal to 5.83 km. In this case, as earlier, it was considered $(H_{min})_{zon}=H_{\kappa}$.

Again let us note that when the optimum program of control is first type program (containing izovysotnyy phase), occurs descent from constraint inside the permissible region of phase coordinates, i.e., to the side of the increase flight altitude.

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The comparison of the optimum program of control with the program, which envisages traffic DV to the end of the horizontal phase with $H=H_{\kappa}$ shows (Fig. 3) that at the optimum control the magnitude of the final rate proves to be substantially less, i.e., gain because of optimization it is sufficient by weight. For example for DV with $p_{\chi}$=350 kgf/m², $K_0$=0.3, $H_k$=6 the km losses in the magnitude of the final rate in flight with H≡$H_k$ they compose 420 m/s.

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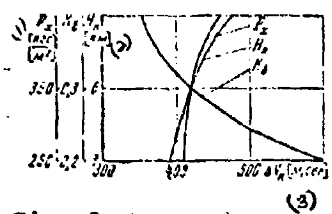

Fig. 3.

Key: (1) kgf/m². (2) km. (3) m/s.

Let us examine, as affects the magnitude of the final rate of change in the altitude of the conditional pericenter of the trajectories of entrance, and also

the designed-ballistic parameters DV ($P_x$ and $K_0$) and the minimally permissible flight altitude at the optimum control of the final rate of descent. The dependences, presented in Fig. 4, show that the magnitude of the final rate in practice does not depend

on the altitude of the conditional pericenter of the trajectory of the entrance within the limits of the operational corridor. As one would expect, the increase

loads on frontal surface and the minimally permissible flight altitudes DV above the surface of planet and the decrease

lift-drag ratio lead to an increase in the final rate. Thus, for instance, increase $P_x$ from 200 to 500 kgf/m²

leads to increase in $V_K$ from 450 to 720 m/s, an increase $(H_{\text{доп}})_{\min}$ with 3 to 9 km leads to change in $V_K$ from 465 down to

656 m/s, and decrease $K_6$ from 0.5 to 0.3 - to increase in $V_K$ from 480 to 592 m/s.

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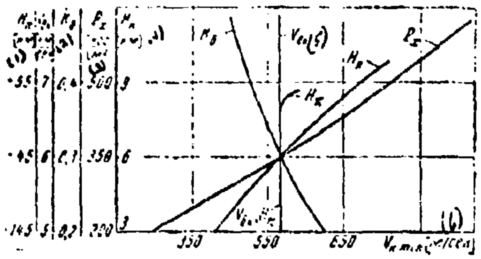

Fig. 4.

Key: (1) km. (2) km/s. (3) kgf/m². (4) km. (5) vkh. (6) m/s.

Evaluation of the effectiveness of the optimum control. The obtained above materials make it possible to evaluate the effectiveness of the optimum control in comparison with program $K_0$=const. Fig. 5 depicts te dependence $\delta V_K$ on $P_X$ and to $K_0$ during a reduction DV within operational reentry corridor. It is evident that for DV with the assigned characteristics the greatest effect is achieved during traffic KA near the middle of operational reentry corridor, and smallest - during traffic near lower boundary. So, for DV with $P_X$=350 kgf/m² and $K_0$=0.3 the maximum gain $\delta V_K$ composes 170 m/s with $H_\pi$=-80 km, but minimum -36 m/s with $H_\pi$=-170 km.

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The effect of the use of the optimum control grow/rises with an increase of $K_6$ increases $P_x$ weakly affects magnitude $\delta V_k$.

So, with increase in $K_6$ from 0.3 to 0.5 the value $\delta V_k$ grow/rises from 170 to 400 m/s, and during change $P_x$ from 350 to 550 kgf/m² it decreases from 170 to 130 m/s.

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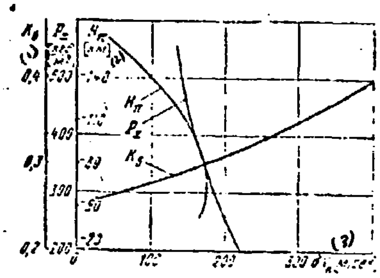

Fig. 5.

Key: (1) kgf/m². (2) km. (3) m/s.

The carried out investigations show that in each concrete case it is necessary to evaluate energy expenditures on active braking and by weight of descent control system before giving preference to the simple or complex view of descent.

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