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DISCRETE ALGORITHM FOR CONTROLLING THE FINAL DESCENT VELOCITY OF SPACE VEHICLES IN THE ATMOSPHERE OF MARS

by

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

FOREIGN TECHNOLOGY DIVISION

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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
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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.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

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

Russian	English
rot	curl
lg	log

DISCRETE ALGORITHM FOR CONTROLLING THE FINAL DESCENT VELOCITY OF SPACE VEHICLES IN THE ATMOSPHERE OF MARS

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

An analysis is made of a discrete algorithm for controlling the final descent velocity of space vehicles (KA) [KA] in the atmosphere of Mars. This can be realized by simple automatic devices. Control of the vector of lift is carried out by means of changing the roll attitude (i.e., the effective component of lift). The control algorithm makes use of the lines of change-over which are stored in the on-board computer. Numerical results are presented from the calculation of the effectiveness of the control algorithm. It is shown that the control algorithm can be used in the construction of systems for control of the final descent velocity for a wide class of landers (SA) [CA] and for different entry velocities.

In work [1] data were presented concerning the optimal control of the final descent velocity of a space vehicle in the atmosphere of Mars. In particular it was shown that for a certain class of landers the optimal control program (or close to it) is a program of single change-over of "effective" quality ($K_{эф}=K_б \cos\gamma$). This program is realized quite readily by simple means [2]. However, the program of control with a single change-over of $K_{эф}$ has limited application, since it can be used only for a comparatively narrow class of landers with low values of reduced load on the front surface $P_x \geqslant 250$ kgf/m^2 and magnitude of lift-drag ratio $K_\sigma \leqslant 0.3$. Figure 1 shows the dependence of final velocity on load on the frontal surface in the case of different programs for control of roll attitude. Along with this, the investigations showed that for a wide class of landers ($P_x \geqslant 250$ kgf/m^2 and $K_\sigma \geqslant 0.3$) the minimal value of final velocity is realized when using a simple program of double change-over of "effective" quality. Below we will consider a discrete algorithm of control which incorporates a twofold transfer of quality $K_{эф}$.

We will accept that the means of navigation ensure an accuracy of guidance which is sufficient for entry into an operational approach corridor [1]. Just as previously [1]-[3], in all cases we will assume that the minimal permissible altitude of flight of the lander above the surface of Mars $H_{min\ доп}$ is no less than the altitude of the beginning of operation of the soft landing system:

$$H_{min\ доп} \geqslant H_к. \qquad (1)$$

When using a program of twofold transfer of quality a lander enters the atmosphere with $K_{эф}=+K_\sigma$ ($\gamma=0$), after a certain time follows the transfer $K_{эф}=-K_\sigma$ and then again to $K_{эф}=+K_\sigma$. The moments of transfer are selected from the condition of obtaining $V_{к\ min}$ with the simultaneous fulfillment of limitation (1).

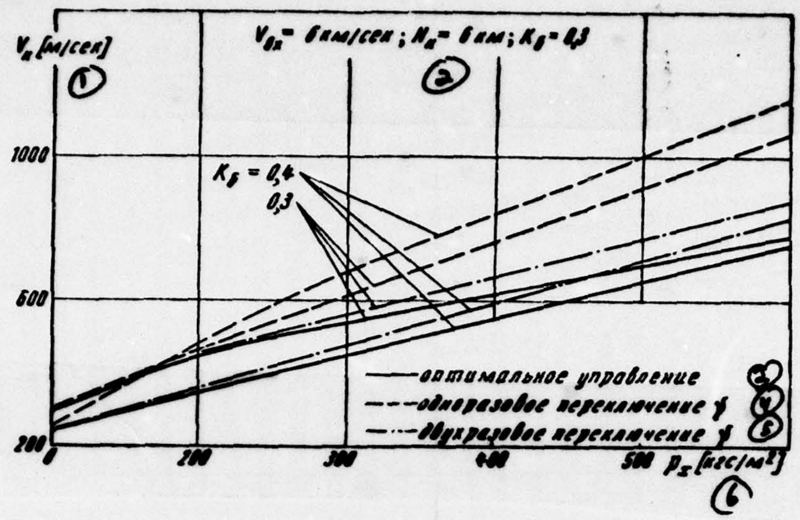

Figure 1.

Key: (1) $V_{\text{к}}$ [m/s]; (2) $V_{\text{вх}}$ = 6 km/s; $H_{\text{к}}$=6 km; K_{σ}=0.3; (3) optimal control; (4) single change-over γ ; (5) twofold change-over γ ; (6) p_x[kgf/m^2].

For realizing the program of twofold change-over it is necessary in each specific case to be able to determine the two points of change-over by using on-board devices. This can be realized by using two lines of change-over which are stored on board the lander. The method of selection of the lines of change-over is analogous to that described previously for the case of a single change-over of quality [2]. As an example we will consider the algorithm for twofold transfer for controlling the final descent velocity $V_{\text{к}}$ of a lander with P_x=350 kgf/m^2 and K_{σ}=0.3. The lines of change-over for this case are shown in Figure 2 in the form of dependences of acceleration $n_{xn}(V_{sn})$ and apparent velocity $t_n(V_{sn})$ [2]. It is evident that the lines of change-over $t_n(V_{sn})$ have a simpler form than $n_{xn}(V_{sn})$, and accordingly they can be approximated more easily by polynomials of the 1st and 2nd degree. Considering this fact, and also the fact that the method of assigning the lines of change-over has virtually no influence on the magnitude of $V_{к}$ [2], subsequently we will assume that the lines of change-over on board the lander are assigned in the form $t_n(V_{sn})$.

For this particular case the lines of change-over shown in Figure 2 can be approximated in the following manner. The line of change-over, determining the moment of the first transfer - by one straight line:

$$t_{n\,1} = a_1 V_{sn} + b_1,$$

where a_1 = -11,111 s^2/m, b_1 = 101,666 s.

The line of change-over, determining the moment of the second transfer - by three straight lines:

$$t_{n\,21} = a_{21} V_{sn} + b_{21} \; (V_s < V_{s1}),$$

where a_{21} = -113,461 s^2/m, b_{21} = 481,942 s, V_{s1} = 3.45 km/s;

$$t_{n\,22} = a_{22} V_{sn} + b_{22} \; (V_{s1} \leqslant V_s \leqslant V_{s2}),$$

where a_{22} = -925 s^2/m, b_{22} = 3191,25 s, V_{s2} = 3.47 km/s;

$$t_{n\,23} = a_{23} V_{sn} + b_{23} \; (V_s > V_{s2}),$$

where a_{23} = 100 s^2/m, b_{23} = - 275 s.

The length of the time interval Δt between the two moments of change-over $k_{\text{эф}}$ for each type of lander depends significantly on the altitude of the conditional pericenter of entry trajectory H_{π}. Thus, for example, for the lander being considered in the case of movement near the upper boundary of the corridor Δt has the greatest value and comprises approximately 70 s. A reduction of H_{π} leads correspondingly to a lessening of the time interval between the two transfers $K_{эф}$ right up to the complete disappearance of it during movement of the lander on the lower boundary of the approach corridor $H_{\pi}^{н}$. In the last case the craft is moving on the entire descent trajectory with an unchanged value $K_{эф} = + K_{\sigma}$.

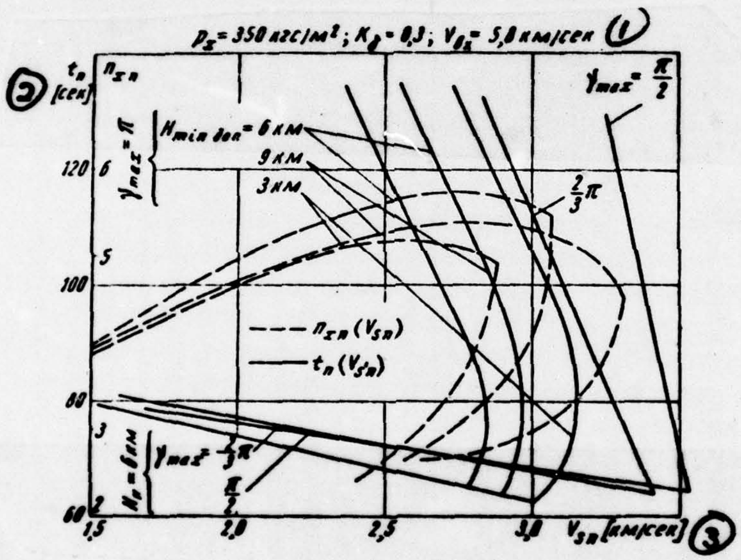

Figure 2.

Key: (1) p_x=350 kgf/m^2; K_{σ} =0.3; $V_{вх}$=5.8 km/s; (2) t_n [s]; (3) V_{sn} [km/s].

The table contains the results of an appraisal of the effectiveness of functioning of the algorithm. Also presented there are the maximum magnitudes of the main perturbations.

Table

P_x=350 kgf/m^2; $\gamma_{max}=\pi$; K_σ =0.3; $H_к$=6 km; H_π = -70 km; $V_{вх}$=5.8 km/s.

(1) Вид возмущения	(2) Диапазон возмущения	(3) $V_к$ [м/сек]
$\Delta H_к$	+100 −100	646 598
$\Delta V_{вх} = \pm 100$ м/сек (4)	+100 −100	639 647
$\Delta P_x = \pm 0{,}1 P_x$ кгс/м^2 (5)	+35 −35	670 604
$\Delta K_б = \pm 0{,}1 K_б$	+0,03 −0,03	633 675

Key: (1) Type of perturbation; (2) Range of perturbation; (3) $V_к$, [m/s].

It is evident that the use of the proposed algorithm makes it possible to work out all the perturbations quite well. Mathematical expectation $M(V_к)$ and triple mean square deviation of the final velocity $\Delta V_к=3\sigma$, determined with the possible combined action of all the perturbations according to the method of B. G. Dostupov [1], [4], comprise correspondingly $M(V_к)$=638 m/s and $\Delta V_к$=45 m/s.

The possible error in the operation of the algorithm for control of final velocity does not exceed 60 m/s in comparison with "ideal" control (instantaneous transfer of the lander for bank, absence of instrument errors, etc.), and 120 m/s in comparison with optimal control (see Figure 1).

It is necessary to note that the minimum flight altitude for the lander on a perturbed trajectory can take values which differ from the assigned $H_{min\ доп}$. Thus for the example being considered the magnitude of mathematical expectation of the minimum flight altitude under the possible total action of all perturbations comprises $M(H_{min})=6.2$ km, and the magnitude of the triple mean square deviation $3\sigma(H_{min})=0.88$ km.

$P_x=350$ kgf/m²; $K_\sigma=0.3$; $V_{вх}=5.8$ km/s.

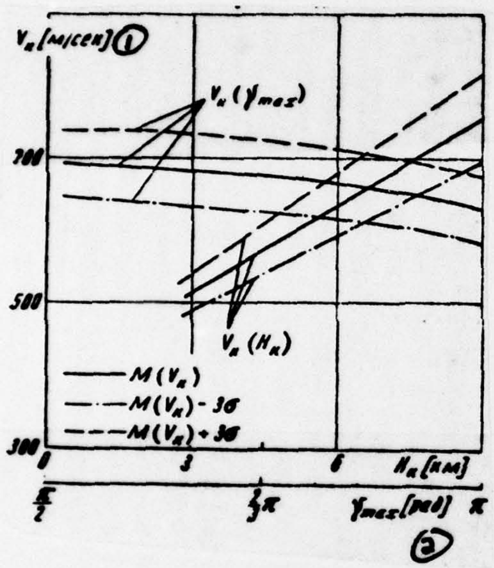

Figure 3.

Key: (1) $V_к$ [m/s]; (2) [rad].

Now let us consider how the change in the maximum magnitude of the roll attitude γ_{max} and the minimal permissible altitude of flight above the surface of Mars influence the accuracy of performance of the control algorithm. As is evident from Figure 3, a reduction of γ_{max} (in the case of the corresponding change of the lines of change-over, see Figure 2) leads to an increase of $M(V_к)$, and in this case the magnitude of 3σ remains virtually unchanged. Thus, for example, with a change of γ_{max} from π to $\pi/2$ the magnitude of $M(V_к)$ increases from 638 to 697 m/s, and $\Delta V_к=3\sigma$ from 45 to 50 m/s. An increase in the minimal permissible flight altitude leads to an increase of $M(V_к)$ and $\Delta V_к$. Thus with a change of $H_{min\ доп}$ from 3 to 9 km (lines of change-over for these cases are shown in Figure 2) the magnitude of $M(V_к)$ increases from 518 to 757 m/s, and $\Delta V_к$ from 23 to 58 m/s. Thus the materials presented testify to the sufficiently high effectiveness of the algorithm with two lines of change-over for landers with $P_x=350$ kgf/m^2 and $K_\sigma=0.3$.

Now we will consider the possibility of using the algorithm of twofold transfer $K_{эф}$ for landers with the designed ballistic parameters: 300 kgf/m$^2 \leqslant P_x \leqslant 600$ kgf/m^2, $0.3 \leqslant K_\sigma \leqslant 0.5$ in the range of entry velocities of 5.5 km/s $\leqslant V_{вх} \leqslant$ 7.7 km/s.

During the investigation of the accuracy of control for each specific case their own lines of change-over were calculated. The results, based on the appraisal of the accuracy of control depending on load on the frontal surface of the lander, lift-drag ratio, and entry velocity, are given in Figure 4. It is evident that an increase in the load on the frontal surface has practically no influence on the accuracy of control, and an increase in the lift-drag ratio worsens it somewhat. Thus, for example, with an increase of P_x from 350 to 550 kgf/m^2 ($K_\sigma=0.3$; $V_{вх}=5.8$ km/s) $\Delta V_к$ changes from 45 to 50 m/s, and with an increase of K_σ from 0.3 to 0.5

(P_x=350 kgf/m^2, V_{BX}=5.8 km/s) ΔV_H changes from 45 to 60 m/s. This is explained by the fact that in all cases the magnitude of relative error in the lift-drag ratio was selected the same - 10%. With an increase of quality there is an increase in the absolute magnitude of error, which leads to an increase in the scattering of final velocity.

As it should be expected, the magnitude of mathematical expectation of final velocity depends considerably on the reduced load on the frontal surface, and an increase of P_x leads to an increase of $M(V_k)$. Thus, if for a lander with P_x=350 kgf/m^2 (K_σ =0.3, V_{BX}=5.8 km/s) $M(V_H)$=638 m/s, then for a lander with P_x=550 kg/m^2 the magnitude of mathematical expectation of final velocity increases to 842 m/s. With an increase of lift-drag ratio the magnitude of $M(V_H)$ initially drops, and then, beginning with a certain value of K_σ, is virtually unchanged. Thus, with an increase of K_σ from 0.3 to 0.4 (P_x=350 kgf/m, V_{BX}=5.8 km/s) $M(V_H)$ is reduced from 638 to 560 m/s, and with a further increase of K_σ from 0.4 to 0.5 $M(V_H)$ is reduced all told by 7 m/s. It follows from here that an increase of the lift-drag ratio above 0.5 for a lander, which is being controlled by the roll attitude, is not advisable.

It is evident from the data given in Figure 4 that an increase of entry velocity has a weak influence of the accuracy of control. Thus, for example, with an increase of V_{BX} from 5.8 to 7.5 km/s ΔV is changed from 43 to 35 m/s(for landers with P_x=350 km/s^2 and K_σ=0.3). It is also evident that with an increase of entry velocity the magnitude of mathematical expectation of final velocity is reduced somewhat. For example, with an increase of entry velocity from 5.8 to 7.5 km/s $M(V_к)$ is reduced from 638 to 600 m/s.

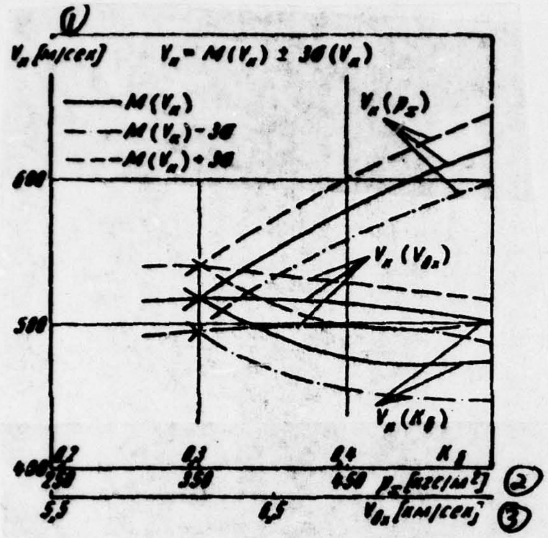

Figure 4.

Key: (1) [m/s]; (2) [kgf/m^2]; (3) [km/s].

Thus the materials presented show that the control algorithm which utilized the lines of change-over can be used in the construction of systems for control of final velocity for a wide class of landers and for different entry velocities. In this case the control algorithm ensures an accuracy of no worse than 50 m/s, and the increase in final velocity in respect to optimal control comprises 120 m/s on the average.

Submitted 19 Oct 1971

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