PRELIMINARY ANALYSIS OF THE BALISTIC PARAMETERS OF A PENETRATOR FOR ECOLOGICAL STUDIES

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1. Necessity

Quite often, the necessity of making some hardware geophysical and ecological studies in hardly accessible places of the Earth arises. Examples of such places are the active volcanic areas, the epicentres of calamitous earthquakes, the polar and desert areas, the radiation-hazardous areas (for instance, the areas of nuclear-power-plant failures), the flooded areas, the gas-penetrated areas, the areas with thick snow cover, etc. In all these cases, the instalment of the relevant equipment involves a lot of difficulties and risks for the engaged people, and very often it is even impossible.

To a certain extent, the problem can be solved by using a penetrator with geophysical and ecological equipment mounted in it. Usually, The penetrator consists of two parts. When launched by an aircraft, in most cases, its basic body penetrates the ground. Whereas the depth of penetration depends on a number of factors: the velocity at the moment of accessing the ground, the mechanical characteristics of the ground, the geometric characteristics of the fore part of the penetrator, its mass etc. The other part of the penetrator remains above the Earth's surface, mainly with purpose of providing reliable radio connection. Having in mind the fact that the goal here is to fix the device into the ground, rather than penetrate it (see item 4), the term "penetrator" is somewhat provisional.

2. Prerequisites

One prerequisite for the development of a penetrator for ecological studies was the studies of the three-component penetrator accelerometer for studying the Mars planet under the "Mars'94" project [1,2]. Another important prerequisite was the tiny and minimal-power-consumption means of telemetric data transfer.

Naturally, the scientific tasks and the conditions for penetration of Mars's surface differ in many ways. They depend on both the technical and technological possibility for launching the penetrator (height, initial velocity, trajectory, velocity of accessing the ground, mass and geometric characteristics of the penetrator, etc.), and the characteristics of the atmosphere and the ground at the site of penetration of Mars or the Earth, respectively.

3. Scientific program

The concrete scientific program for ecological studies with a penetrator depends on the concrete object, goals, and tasks. Hardly any discussion is needed to substantiate the statement that ecological studies are, in their essence, geophysical studies, since they are aimed at studying the physical and geophysical parameters of the surrounding medium. The same fact refers to the ecological calamities of natural and anthropological origin which are, in fact, extreme changes of these same parameters [3]. For this reason, in most cases, the scientific problems, related to penetrator studies, are studies of some geophysical parameters: temperature, humidity, micro- and macro-seismic oscillations, radiation background, etc.

4. Differences between the penetrator studies of Mars and the Earth

Several fundamental differences between a "marsian" and an "earth" penetrator can be pointed out.

The purpose of the marsian penetrator is to penetrate to relatively greater depth, so that it can operate within smaller temperature range, having in mind the marsian diurnal range, which is about 50°C. However, the penetration to greater depth H necessitates greater initial velocity of penetration V_o. But this greater velocity involves greater shock acceleration, the value of which is limited by the shock-resistance of the scientific-research and official equipment. On the other hand, the greater shock generates seismic waves with greater amplitude range, which provides a more effective amplitude and frequency registration of the reflected waves. Besides, the greater penetration time t provides greater resolution of registration during the penetration process [4].

With the earth penetrator, the change of temperature is not so important to the equipment's operation. The penetrator for geophysical and ecological studies must not penetrate to a great depth. It must be solidly fixed into the ground. As for the artificial generation of seismic waves, dropping from an aircraft of special weights with prescribed mass, from prescribed height, and a prescribed distance away from the research penetrator, can generate them.

In the marsian experiment, the penetrator is launched from the board of an orbital station - an artificial satellite of Mars, which makes it rather more difficult to technologically provide the prescribed velocity with which the penetrator must access the marsian surface, i.e. the velocity V_o.

In the Earth version, this latter velocity can be provided for with great enough accuracy since the launch of the penetrator from an aircraft can be performed precisely from the prescribed height, guaranteeing the prescribed velocity in accessing the Earth's surface.

5. Movement of the penetrator through the atmosphere

5-a. Movement of the mass centre and velocity of accessing the Earth's surface

The position of a body in space is determined by six parameters: 3 co-ordinates of the mass centre (MC), and 3 rotation angles. The movement of the body is determined if the time function of these parameters is known. Often, rotation is assumed to be independent on the movement of MC. In the general case, however, this is not true.

The movement of the MC of a body, moving freely through the atmosphere, is described by the following differential equation:

(1) $$\mathbf{m}\frac{d\vec{\mathbf{V}}}{dt} = -\hat{\mathbf{C}}\vec{\mathbf{V}} + \vec{\mathbf{g}}$$

where *m* and ***V*** are respectively the mass and the velocity of MC, *g* - the Earth's acceleration.

Besides on the parameters of the environment (density, viscosity etc.), the coefficient *C* depends as well on the orientation of the velocity vector as to the body. In the general case, this coefficient is a tensor (matrix), and obviously, the movement of MC depends on the body's rotation.

If the body has a symmetry axis, and the velocity of MC is parallel to this axis, then *C* is a scalar (a unit matrix multiplied by a scalar). In this case, *C* is a function of:

1) Mah's number ($M=v/a$, *a* being the sound velocity);

2) air density ρ;

3) the form of the body;

4) the velocity of the body.

The dependence on the other parameters (for instance, viscosity) can be neglected [5]. Then we can write: $C=k.\rho.S.V.C_x(M)$, where $S=\pi.d^2/4$ - a cross-section, perpendicular to velocity (middle section); $C_x(M)$ is a function, called resistance law, which depends on the general form of the body (but not on its size), and is usually provided in table form; k is a coefficient, depending on the concrete size (determined experimentally, and depending, in the general case, on the Mah's number, too, but in the calculations assumed to be constant).

If we replace $C(M)=k.\pi.d^2.V.C_x(M)/8m$, we can write (1) in the following way:

$$\frac{d\vec{V}}{dt} = -C(M).\vec{V}+\vec{g} \tag{2}$$

If we choose a co-ordinate system with axis Oy directed vertically upwards, horizontal axis Ox such that the velocity be lying in the xOy plane, and axis Oz supplementing the coordinate system to a right-oriented one, then (2) can be written as follows:

$$\begin{cases} \frac{dV}{dt} = -C(M)\rho V^2 - g\sin(\lambda) \\ \frac{d\lambda}{dt} = -\frac{g\cos(\lambda)}{V} \\ \frac{dx}{dt} = V\cos(\lambda) \\ \frac{dy}{dt} = V\sin(\lambda) \end{cases} \tag{3}$$

where λ is the angle between the velocity vector V and the axis Ox. In the case of a body falling downwards, $\lambda < 0$ and the earth gravitation force $g\sin\lambda$ and resistance $C(M).\rho.V^2$ are opposite whereas with a body rising upwards, $\lambda > 0$ and the forces are parallel.

In the general case, the system of differential equations (3) can be solved only numerically at least because $C_x(M)$ is provided in table form. Besides, the density ρ depends on height, in a complex way on temperature, season, and solar activity. The sound velocity (and from there, M) depends on temperature and density ρ. Temperature is a function of height etc. Tables and algorithms for the determination of $C_x(M)$ and ρ are given in [5]. The coefficient k is determined experimentally.

Here, an analytical solution of system (3) for one simple case is suggested, namely for the case of launching the penetrator from an airplane. This has a number of advantages since it provides a better choice for the penetration site, launching from a smaller, and more precisely determined height, tracing the process of launch and penetration etc. The use of an airplane is better justified for a number of organizational, technological, and economic reasons, too, moreover when regions of ecological calamities are concerned.

In this case, the movement proceeds only along the vertical, i.e. $\lambda=-\pi/2$, the velocity $\boldsymbol{V}$ changes a little and within limits where $C_x(M)$ remains nearly constant (these are velocities up to 0,7 of the sound velocity: $V < 0{,}7a$), the body passed a distance within which the change of the density of the medium ρ is insignificant. Then in (3), $C(M)=c=$const, and (3) is transformed into:

$$(4)\qquad \begin{cases} \dfrac{dV}{dt} = -cV^2 + g \\ \dfrac{d\lambda}{dt} = 0 \\ \dfrac{dx}{dt} = 0 \\ \dfrac{dy}{dt} = -V \end{cases}$$

The second and third equations in (4) show that the movement will remain directed along the vertical. If we assume the initial velocity V=0, the first equation of (4) will have the following analytical solution:

$$(5)\qquad V(t) = \sqrt{\frac{g}{c}}.\,tgh(t\sqrt{gc})$$

After substituting (5) in the last equation in (4) and assuming the initial shift to be zero, we obtain:

$$(6)\qquad y(t) = -c^{-1}\ln(ch(t\sqrt{gc}))$$

It can be shown that $\mathbf{V(t)} \xrightarrow[\mathbf{c} \to 0]{} \mathbf{gt}$, and $\mathbf{y(t)} \xrightarrow[\mathbf{c} \to 0]{} \mathbf{gt}^2 / 2$. Thus, with negligibly small aerodynamic coefficient, (5) and (6) are the solutions for a free-falling body.

The solution here obtained has at least two advantages over the numerical integration over (4): i. it can be found by calculator; ii. it is not sensitive to the chosen method or step of integration.

In this case, the most essential thing is that equations (5) and (6) allow for the time to be excluded, and the velocity to be determined as function of height. As shown in [3], under given physic-mechanical properties of the ground, and geometric characteristics of the penetrator, the penetration depth H depends directly on the velocity V_p, with which the earth's surface is accessed.

If t gc be found from (6) and substituted in (5), we get:

(7)
$$\mathbf{V} = \mathbf{exp(c.h)}\sqrt{\frac{\mathbf{g}}{\mathbf{c}}}\sqrt{\mathbf{exp(-2.c.h)} - 1}$$

where h is the launch height.

With negligibly small aerodynamic coefficient, we have $\mathbf{V} \xrightarrow[\mathbf{c} \to 0]{} \sqrt{2\mathbf{gh}}$, which is the well-known relationship for a free-falling body.

To approximately calculate the relationship $V=V(h)$, the following values are assumed: sound velocity a=340,294 m/s, mean atmospheric density ρ=1,225 kg/m^2, resistance function $C_x(M)$=0,255 (if 0<M<0.7). These are the average atmospheric parameters for heights up to 1000 m and temperature T=290 K [5].

In Fig.1, the relationship V=V(h) according to (7) is shown, with aerodynamic coefficient ($\mathbf{C(M)} = \mathbf{k}\rho\pi\mathbf{d}^2\mathbf{C_X(M)} / 8\mathbf{m} = 3.10^{-4}\mathbf{k}$), penetrator diameter **d=25 cm**, **m=25** kg). For comparison, the curves for k =1 (curve 2), k =2,5 (curve 3) and the case of a free-falling body (curve 1), are shown.

As might be expected, the atmospheric influence on velocity increases with increase of the launch height.

The error that would be made had the atmospheric resistance been not accounted for, is illustrated in Fig.2 for three different launch heights: 800 m (curve 1), 500 m (curve 2), and 300 m (curve 3). On the X-axis, the value of the form coefficient **k** is marked. As it was said already, it depends on the concrete size of the penetrator and should be determined experimentally. For most elongated bodies, its value is between 0,1 and 3.

5-b. Fluger stability of the penetrator

An essential condition is that the penetrator must access the earth's surface with its fore part, the angle of ground attack being close to 90^o. It is well-known that a body, moving through the atmosphere, as a result of the generated aerodynamic moments, displays the tendency to rotate itself around its axes. To diminish this rotation, the penetrator must rotate about its vertical axis. Thus, as a result of the law for conservation of the quantity of motion, it will try to preserve the direction of this axis. Besides, it is necessary that the centres of gravity and aerodynamic pressure be far from one another, the centre of gravity being lower than the centre of aerodynamic pressure.

These requirements naturally impose an elongated form for the penetrator, as well as the eventual provision of stabilizers.

6. Conclusion

With other values of m and d, the values obtained for the coefficient of aerodynamic resistance c are different. For instance, with the standard aviation bomb, in which m is considerably greater than the value assumed in the present modelling, and the ratio between the length L and the diameter of the middle section d_m is: $L/d_m \cong 5$, the result shows that air resistance can be neglected. The modelling made here provides the option to decide where the above value can be neglected, depending on the penetrator's mass-size characteristics and launch conditions.

The present works lays the beginning of a pioneer (in the authors' estimation) development to the design of a technical mission for the construction of a penetrator for geophysical and ecological studies, as well as for the formulation of the scientific problems in these studies. We consider the performed preliminary analyses and obtained first results to be merely the basis for further continuation of the development.

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Preliminary Analysis of some Ballistic Parameters of a Penetrator for Ecological Studies

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(S u m m a r y)

Quite often, it is necessary to perform some instrumentation geophysical or ecological studies at hardly accessible sites of the Earth: active volcanoes, epicentres of calamitous earthquakes, polar or desert areas, areas with radiation danger, flooded territories, gas-invaded areas, areas covered by deep snow cover, etc. In all these cases, instrumentation mounting is related with great difficulties and much risk for the people, and sometimes it is even impossible.

The paper is dedicated to an optional solution of the problem, namely the design of a penetrator for ecological and geophysical studies. Based on the expertise wiith the development of a penetrator accelerometer for studying of the Mars planet, analysis and preliminary calculations of some major technical-operational parameters of a penetrator with geophysical equipment mounted on it are made. The obtained results can be considered as the first step in this direction. They provide grounds for the development of a technical statement and a relevant research program.

$C_x(0 \div 0.7) = 0.255$

$\circ \circ$

$\left(C(M) = k \rho \pi d^2 C_x (0 \div 0.7) / 8m = 3.10^{-4} k \right)$

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$C(M) = k \rho \pi d^2 C_x () / 8m = 3.10^{-4} k$