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Nano-Accelerometers for Acceleration Measurement of Objects Moving in the Rarefied Gaseous Environments

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Abstract **- Solution of the nano-acceleration problem of solid body in the diluted gas environment is considered. To resolve the problem, the interaction effect principle of kinematic solid bodies in sparse atmosphere is used. The bodies differ by weights, midsection areas, and facing resistances in the environment, while there is a variety of moving options for the interaction of solid bodies in sparse atmosphere in general. A brief mathematical survey of algorithms, which determine accelerations of moving objects in the diluted gas environment, is presented. The nano-accelerometer algorithm for the object with two solid bodies in case, where the body weights are constants or changed occasionally in time, is studied. Specifications of the body orbit under external forces in the sparse gas environment are received depending on the orbit correction intervals. Modelling of the object with nano-accelerometer is presented by means of MatLab/Simulink software. Investigation results confirm the effectiveness of using nano-accelerometer for this class of real-world objects in the diluted gas environment.**

Keywords **– body interaction principles, braking and drift accelerations, nano-acceleration measurement, nano-accelerometer, rarefied gaseous environment**

I. Introduction

The problem of determination of acceleration value for objects moving in the rarefied gaseous environment is substantial for various areas of science and technology (ballistic gravimetry, micro-accelerometry, experimental gas and aerodynamics of rarefied environments, etc.). Thus, it is essential for the latest technologies to be related to space technology. Thus, for example, poor accuracy in knowledge of these values (accelerations) for driving space vehicles (SVs) leads finally to comprehensive decrease in solution quality on main objectives. Now, the level of solving the problem being considered does not correspond to the requirements in practice, as for its solution only calculus is applied, which is distinguished through excessive complexity of calculations and acceptable accuracy for objects of constant weight and simple shape only [1].

Therefore, in practice the acceleration determination of moving SVs is made by means of periodic “consensus” of their values with the results of orbit radio monitoring. Effectiveness of such “consensus” is insignificant, as this method is indirect and contains all disadvantages of indirect measuring methods due to the fact that the results of measurements include various “confounding” factors, which are almost incapable of selection by means of the existing procedures of telemetric processing [2]. Therefore, searching for new approaches to such a solution represents theoretical and practical interest.

The present article envisages one of such possible and essentially new solution methods of acceleration determination of objects moving in the rarefied gaseous environment. It is based on a new principle of object motion acceleration in the rarefied gaseous environment named ‘specific and differential’. This method is based on the use of interaction effect of kinematically connected rigid bodies moving in the rarefied gaseous environment and distinguishing among themselves through drag coefficients against this environment [2, 3]. On the basis of this method, a theoretical justification of the algorithm system of motion acceleration determination of various objects having constant and variable mass and dimension characteristics in the rarefied gaseous environment has been performed. As the rarefied environments dragging the motion of objects, analogues of rarefied layers of the upper atmosphere of the Earth in the altitude band from 1500 km and higher are considered; and as the main research objects, which are the focus of the developed method system, SVs of various target purposes appear [3, 4].

Justification of new technical solutions is carried out by the development and research of nano-accelerometer mathematical models considering key parameters of kinematically bound rigid bodies and perturbing factors, which affect them in actual conditions in case of SV motion in low and medium-altitude circumterraneous orbits.

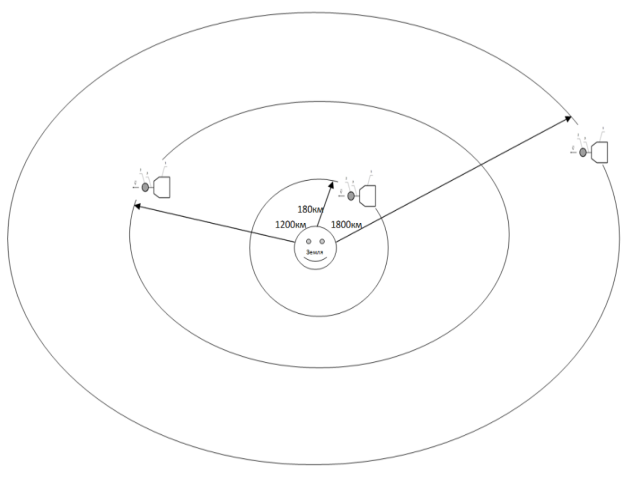

Fig. 1. Scheme of the space vehicle motion

Fig. 1 gives a scheme of SV motion placed into elliptic orbit at a distance of 1800 km from the Earth surface. This scheme shows two more orbits, on which the SV sinks under the influence of external forces arising in case of SV motion in the rarefied gaseous environment. Measurement of braking accelerations and SV sinking values depending on time will be researched with application of nano-accelerometer model [11].

II. Theoretical Basis of Determination of Object Motion Acceleration in the Rarefied Gaseous Environment

A. *Methodology of Determination of Object Motion Acceleration in the Rarefied Environment and the Main Accepted Assumptions*

Taking into consideration the possibility of various versions of rigid body interaction schemes for the rarefied gaseous environment distinguished through quantity of bodies, number, type, nature of used communications and some other aspects, the present article outlines the results of research of a simpler rigid body interaction scheme (Fig. 2 and Fig. 3).

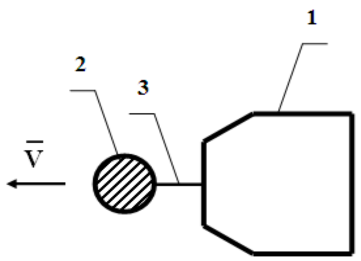

Fig. 2. The first version of the body interaction scheme

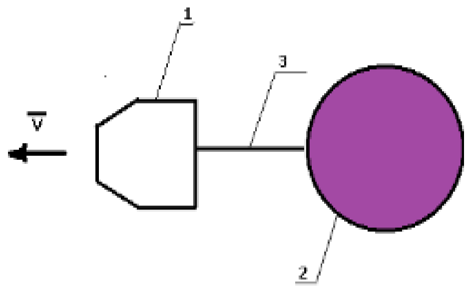

Fig. 3. The second version of the body interaction scheme

where the designations are as follows:

1 – the main body (studied object);

2 – the auxiliary body having normalized and known parameters;

3 – the kinematic connections between interacting bodies.

On the basis of rigid body interaction scheme for the rarefied environment (Fig. 2), an algorithm system for determination of motion accelerations of such a system in the space at constant and variable mass and dimensional characteristics of interacting bodies has been developed. Thus, theoretical justification of the developed algorithms has been carried out within the following assumptions.

1. Interacting bodies (main and auxiliary) are absolutely rigid and have localized masses.

2. The auxiliary body has normalized and a priori known parameters.

3. Kinematic connection has negligibly small mass in comparison with mass of interacting bodies.

4. Distances between the bodies are insignificant and comparable to the sizes of the main body.

5. Continuous medium is rarefied (Knudsen number $K_n >> 1$) and there is a loose molecular flow of interacting bodies, which is the basis of application of the 'specific and differential' principle.

6. Connected bodies move in the rarefied environment at a certain speed $V(t)$ and it is assumed that each of them is affected by drag (drift) force of this environment.

As the distance between interacting bodies is insignificant, it is possible to consider that the rarefied gaseous environment around them is homogeneous during each moment of current time. Besides, for simplicity of the considered model we shall assume that kinematic connection, along which the interaction between bodies occurs, is focused strictly on the speed vector $V(t)$, i.e., lateral forces of drift are negligibly small.

At the same time, in order to avoid unwieldy mathematical equations of object motion in the rarefied environments, in addition, we shall assume that the auxiliary body has one degree of freedom in relation to the main body and can move along the corresponding kinematic connection.

III. Mathematical Model of Accelerometer for Object Motion Acceleration Measurement on the Basis of Interaction of Two Kinematically Connected Rigid Bodies

In order to create a mathematical model of device of object motion acceleration determination on the basis of the interaction scheme of two rigid bodies, we will use the materials given in [12].

It is possible to show the equation of interaction connecting acceleration $y(t)$ of the system of connection of two rigid bodies with force, arising in kinematic connection between them, through parameters of these bodies, through a ratio [2]:

$$y(t) = \frac{h_0 H_0 + h_1 H_1}{m_0 h_1 H_1 - m_1 h_0 H_0} F_1(t) \qquad (2.1)$$

where m_0, m_1 are the masses of interacting rigid bodies;

H_0, H_1 are the body reference areas of interacting bodies;

h_0, h_1 are the drag coefficients of interacting bodies;

$F_1(t)$ is the force of interaction arising in kinematic connection between bodies.

Let us prove the formula (2.1). Singularity of interaction of two rigid bodies, corresponding to specified conditions and indicated previously in Fig. 2 and Fig. 3, consists in the following. As bodies 1 and 2 have various drag coefficients against the rarefied environment, in which they move at a certain speed $V(t)$, an interaction force $F_1(t)$ occurs in kinematic connection 3. Depending on where (ahead or behind) the body with a larger drag coefficient in relation to the body having a smaller drag coefficient is placed, this interaction force will be the compressive force or the tension force.

In particular, if the auxiliary body 2 has a larger drag coefficient than the main body 1, for the option of their connection shown in Fig. 2 the compressive force occurs in communication 3, and for the option of their connection shown in Fig. 3 it will be the tension force. In terms of definiteness and, at the same time, without reducing the generality, we study the laws of interaction of bodies by the example of option of their connection given in Fig. 2. As a result, for the main and the auxiliary bodies the equation of forces will be the following:

$$y_1(t)m_0 + F_1(t) = y(t)m_0, \quad (2.2)$$

$$y_2(t)m_1 - F_1(t) = y(t)m_1, \quad (2.3)$$

where m_0, m_1 are the masses of the main and the auxiliary bodies;

$y_1(t)$, $y_2(t)$, $y(t)$ are the braking or drift accelerations (BDA) of the main body, auxiliary body and the system of two connected bodies on the whole, respectively.

Accelerations are defined by the following ratios [3].

$$y_1(t) = m_0^{-1} h_0 H_0 f(\rho, V, t), \quad (2.4)$$

$$y_2(t) = m_1^{-1} h_1 H_1 f(\rho, V, t), \quad (2.5)$$

$$y(t) = (m_0 + m_1)^{-1}(h_0 H_0 + h_1 H_1) f(\rho, V, t) \quad (2.6)$$

Function $f(\rho, V, t)$ included in formulas (2.4)-(2.6) determines the dependence of BDA of the rigid body on density of rarefied environment $\rho(t)$, in which it moves at a certain speed $V(t)$. For example, in case of rigid body motion in the rarefied gaseous environment this function is defined by the ratio $f(\rho, V, t) = \rho(t)V^2(t)/2$ [7].

On the basis of ratios (2.2) and (2.4), we will receive:

$$f(\rho, V, t) = (y(t) - m_0^{-1} F_1(t)) m_0 h_0^{-1} H_0^{-1} \quad (2.7)$$

Having inserted this expression in (2.6), after simple transformations, we will receive the required formula (2.1), connecting BDA $y(t)$ with force $F_1(t)$ through parameters of interacting rigid bodies. This equation will be called the equation of system interaction of connection of two rigid bodies.

Thus, for completeness of the exposition we will note that a version of interaction of two rigid bodies with occurrence of an ‘eclipse’ process is possible, i.e., when the auxiliary body is in the shadow of the main body (see Fig. 3.)

This justification of sought methods is carried out for the case when bodies do not ‘eclipse’ each other from influence of the rarefied environment, in which they move at a certain speed of $V(t)$. This case can be provided by means of application of specific technical solutions either to the design of the auxiliary body (for example, it is possible to use an auxiliary body in the form of a torus) or to the arrangement of kinematic connections (for example, by application of extension bars).

In the case, when ‘the eclipse’ anyway takes place and no specific technical solutions are applied to exclude it, it is easy to show that the ratio (2.1) is brought to the form, in which ‘the eclipse’ of one body by another is taken into consideration.

$$y(t) = \frac{h_0(H_0 - H_1) + h_1 H_1}{m_0 h_1 H_1 - m_1 h_0 (H_0 - H_1)} F_1(t) \quad (2.8)$$

The ratio (2.8) in more ‘adequate degree’ is described by the options of interaction of rigid bodies presented in Fig. 2 and Fig. 3. It will be applied later by consideration of technical implementation issues of the suggested methods for determination of focused object motion acceleration.

In order to confirm the possibility of technical implementation of the suggested method we will estimate a concrete example of possible modification ranges subjected to $y(t)$ and $F_1(t)$ value measurement. Let us consider it with a reference to low-orbital SV for the case, when the main body (SV) has the weight of 5000 kg and the reference area is 5 m2, and the auxiliary body has the weight of 5 kg and the reference area is 2 m2.

Values of estimates on possible modification ranges $F_1(t)$ and $y(t)$ depending on SV circular orbit altitude with the use of dynamic model data of the atmosphere defined by GOST 22721-77 for the minimum and the maximum of solar activity [5] are given in Table I (columns 2 and 3 of Table 1 specify results without accelerometer application) (for altitudes up to 500 km in columns 2,3). In column 4 of this table, the estimates of acceleration received during the modelling of accelerometer algorithms for the same altitudes up to 500 km are added. The results of modelling confirm high efficiency of the developed techniques and accuracy of acceleration calculations by nano-accelerometer of this class in case of object motion in the rarefied gaseous environments (in low and average circumterraneous orbits).

Here we provide the program of object (SV) acceleration calculation under the influence of forces (with the use of atmosphere dynamic data).

```
F1=10^(-3)*[31.35 64.13 13.96 35.63 4.85 38.48 0.32 6.56 0.03 0.17]; F1'; % F1 for N;m0=5000; h0=2.0; H0=5.0; m1=5.0; h1=2.0; H1=2.0;
y1 = (h0*H0+h1*H1)*F1./(m0*h1*H1-m1*h0*H0);y1',        % y1,m/sec2
ans = [(2.2÷4.5)e-005 (9.8÷25)e-006 (3.4÷27)e-006 (2.3÷46)e-007 (2.2÷12)e-008];
```

TABLE I

ESTIMATED VALUES OF THE FORCE F_1 AND ACCELERATION

Orbit height, km	Range of force, F, mN	Range of braking acceleration, м/sec2	Range of acceleration in system, м/sec2	Differences in acceleration measurement,%
1	2	3	4	5
180	31.35÷64.13	(2.2÷4.5)·10-5	(2.2÷4.5)e-005	0
200	13.96÷35.63	(9.8÷25)·10-6	(9.8÷25)e-006	0
300	4.85÷38.48	(3.4÷27)·10-6	(3.4÷27)e-006	0
400	0.32÷6.56	(2.3÷46)·10-7	(2.3÷46)e-007	0
500	0.03÷0.17	(2.2÷12)·10-8	(2.2÷12)e-008	0

IV. RESEARCH OF DYNAMIC CHARACTERISTICS OF NANO-ACCELEROMETERS WITH TWO RIGID BODIES BY MEANS OF MATLAB/SIMULINK

For an objective assessment of opportunities of the developed acceleration measurement method for rigid body motion in the rarefied gaseous environment and the algorithms implementing this method, some dynamic and precision characteristics of mathematical models of nano- accelerometers of this type have been studied.

The following characteristics are included:

A) Definition of the transfer function (TF) of nano-accelerometer (Wi) and calculation of its dynamic characteristics: impulse(Wi), step(Wi) and lsim(Wi,u,t).

a) Definition of TF (Wi) of nano-accelerometer model for four values of main body weight (m0 = 5000kg, 1500kg, 1000kg and 700kg).

b) The output signal of nano-accelerometer for an arbitrary input signal (for example, a harmonic signal of [u,t]=gensig('sin',5,30,0.1) type for four weight values of the studied object model).

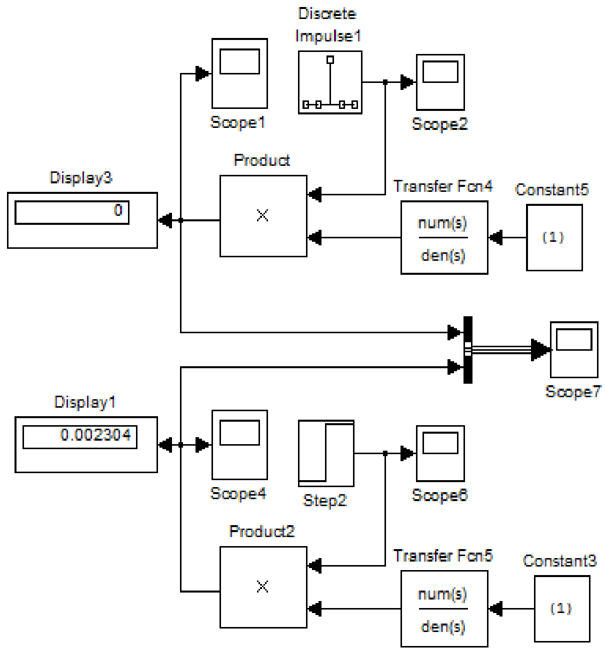

Fig. 4. Calculation scheme of nano-accelerometer characteristics

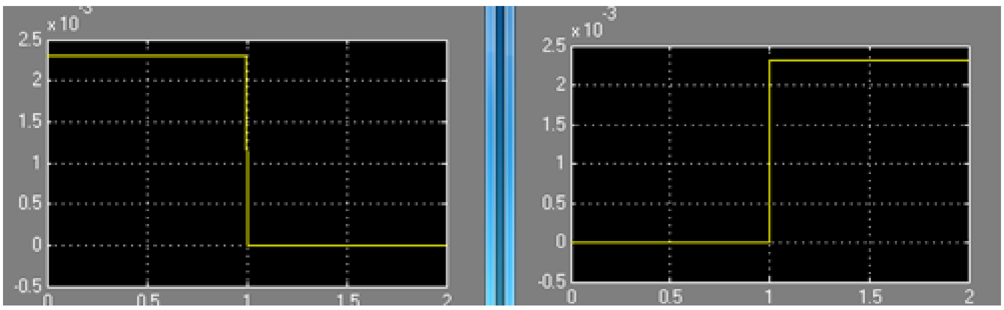

Fig. 5. a) impulse signal for W_{5000} b) step signal for W_{5000}

On the basis of the received nano-accelerometer transfer functions, we will define pulse and transitional functions of W5000, W1500, W1000, W700 models in the SIMULINK system.

The model block diagram for calculation of specified nano-accelerometer characteristics is provided in Fig. 4. Fig. 5a, 5b for W5000 model.

Therefore, the performed analysis of the main dynamic characteristics of nano-accelerometer mathematical model confirms that this device is an ‘ideal’ dynamic system.

B) Dependence of measured acceleration on the weight of the studied object (mo).

In the course of object functioning, its weight constantly changes (engine unit fuel component consumption, separation of research structures and waste blocks of the object) that leads to a change in its motion acceleration.

Dependence characteristics of measured acceleration yi on the weight of the studied object (m0) for the existing force F1 in the range [3.2e-018÷6.413e-002]N are calculated with the use of MATLAB functions. The received results are presented in Table 2 (columns 3,4,5 and 6).

Figures 6a, 6b, 6c specify the results of calculations of acceleration of driving of object for four values of its weight under the influence of force F1 in the following four ranges.

Therefore, schedule analysis provided in Fig. 6a, 6b and 6c confirms a linear dependence of measured acceleration on the interaction force between two rigid bodies in all range of force change for actual weight values of the studied object.

C) Dependence of measured acceleration on random changes of object weight (mo).

In the course of object functioning, a random decrease in its weight is possible. Fig. 7 contains the results of object motion acceleration changes in case of a random decrease in its weight for four options of its rated values (m0i-abs(3*rand(1,36)) under the influence of force F1 in F1 range [3.2e-018÷6.413e-002],N. For the purpose of comparison, this schedule shows characteristics (shown by the dotted line) for the case when the random component in weight change is absent.

These results show that a random decrease in the weight of the studied object in the course of its motion in a circumterraneous orbit does not change the linearity of characteristics of acceleration dependence on the existing force.

Therefore, these results show that a random decrease in the weight of the studied object in the course of its motion in the circumterraneous orbit does not change the linearity of characteristics of acceleration dependence on the applied force.

D) Measured acceleration dependence on random changes of the force existing between interdependent bodies.

In the course of object motion on the orbit, the force of interaction between the studied and the reference bodies has the random component depending on the condition of rarefied gaseous environment in the concrete time interval of motion.

Fig. 8 gives the characteristics of acceleration change in case of random changes in the weight of the object (m0i-abs(3*rand(1.36)) and in the force of F3r=F1+0.02*F1*rand(1.36), affecting the object (solid lines) and for the option when there is no component of the random component weight (dashed lines).

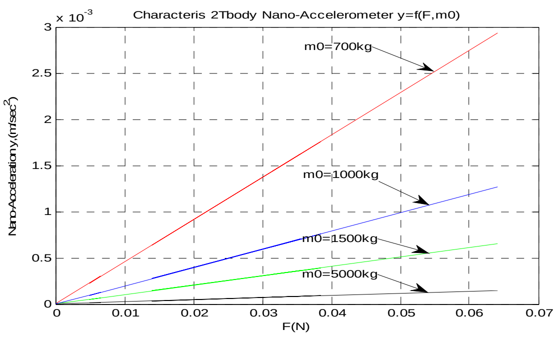

Fig. 6a. Nano-accelerometer characteristics with the function $y_1=f(F, m_0)$

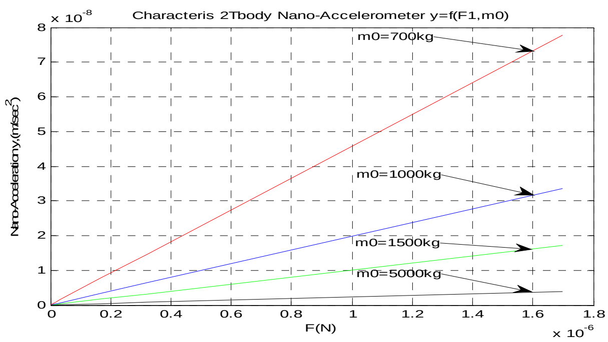

Fig. 6b. Nano-accelerometer characteristics with the function $y_2=f(F_1, m_0)$

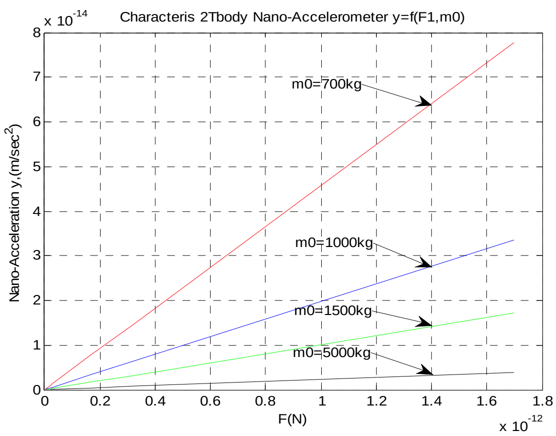

Fig. 6c. Nano-accelerometer characteristics with the function $y_3=f(F_1, m_0)$

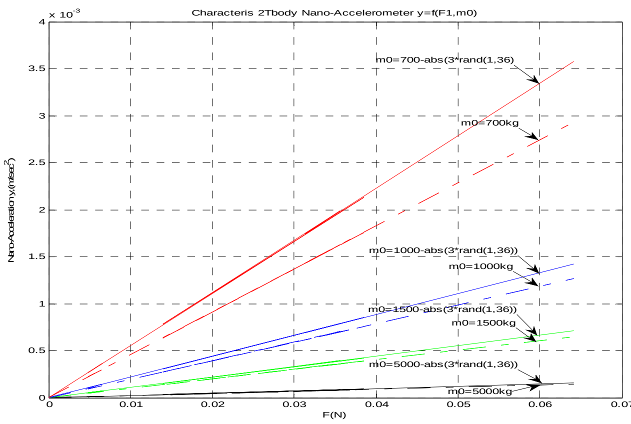

Fig. 7. Nano-accelerometer characteristics with the function $y_4=f(F_1, m_0)$

E) Dependence of object drift value on the applied force in the given time interval for various weights of the studied body.

The main result of external force effect on the object moving in the rarefied gaseous environment is represented in the form of a drift of this object from the orbit. Parameters of the drift value depend on many factors bound to specifics of the program of object motion in the rarefied gaseous fluid.

Therefore, the results show that a random decrease in the weight of the studied object in the course of its motion in the circumterraneous orbit and random fluctuations of the applied force does not change the linearity of characteristics of acceleration dependence on this force.

Table II shows the results of drift value estimation (column 4) of the object with the given weight depending on its stay time (hour, month, year) at the corresponding altitude of the orbit and for the given range of the external forces applied to the object. Results of calculations of object sink value from the orbit for three time intervals, given in Table 2, are proven by calculations in the Simulink modelling. The block diagram of modelling system for object drift from the given orbit for 3 time intervals is provided in Fig. 9. Received results on object sinking in 3 time intervals for altitudes

a)180-500km, b)600-1000km, c)180-1200km are provided in the schedules.

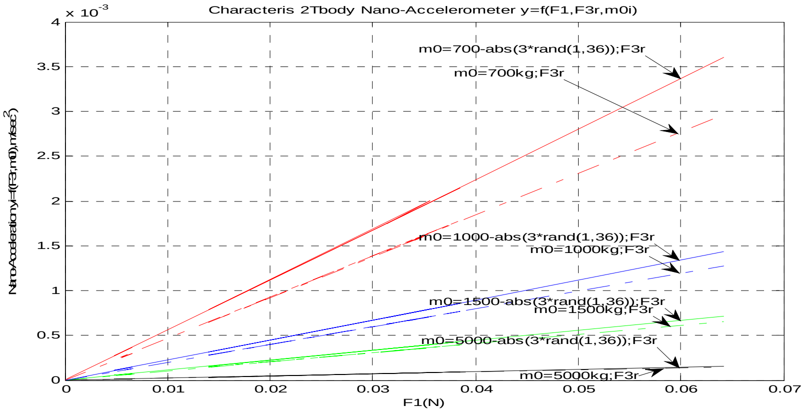

Fig. 8. Nano-accelerometer characteristics with the function $y_5=f(F_1, F_{3r}, m_0i)$

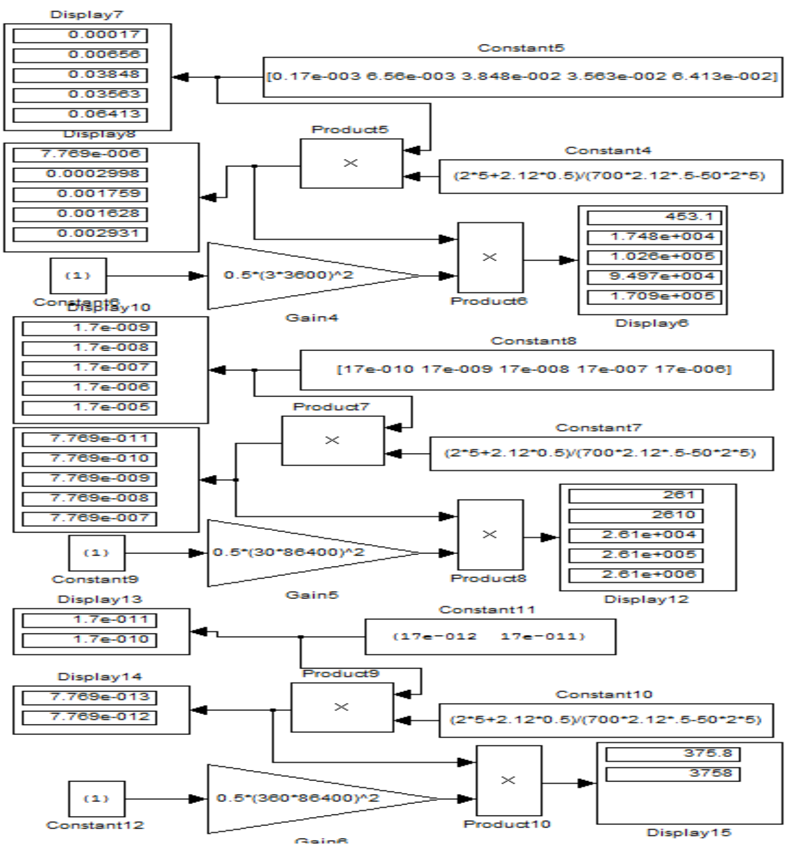

Fig. 9. Scheme of nano-acceleration and drift modelling

TABLE II
RESULTS OF DRIFT VALUE ESTIMATION, DEPENDING ON THE FORCE, WEIGHT AND ACCELERATION

Orbit height, km	**Range of force, F, mN**	**Range of acceleration for m0=5000kg;1500kg;1000kg;700kg , m/sec2**	**Range of orbit drift distance for m0=5000kg; 1500kg; 1000kg; 700kg , км / Drift time, hrs**
1	2	3 4 5 6	7(3) 7(4) 7(5) 7(6)
180	31.35 ÷ 64.13	((7.2÷14.8);(32÷65);(62÷127);(143÷293))e-005	((4.2÷8.62);(19÷38);(36÷74);(83.6÷171)/3 hrs
200	13.96 ÷ 35.63	((3.2÷8.2);(14÷36);(27.6÷70.3);(64÷163))e-005	((1.9÷4.8);(8.3÷21)÷ (16÷41) ÷(37÷95) /3 hrs
300	4.85 ÷ 38.48	((1.1÷8.9);(4.9÷39);(9.6÷76);(22.2÷176))e-005	(0.65÷5.2);(2.9÷23);(5.6÷44);(12.9÷103)/3 hrs
400	0.32 ÷ 6.56	((0.74÷15);(3.3÷67);(6.3÷130);(14.6÷300))e-006	(0.043÷0.88);(0.2÷3.9);(0.37÷7.6);(0.853÷18)/3 hrs
500	0.03 ÷ 0,17	((0.69÷3.9);(3÷17.3);(5.9÷33.6);(13.7÷77.7))e-007	(0.004÷0.023);(0.018÷0.1);(0.035÷0.2);(0.08÷0.45)/3 hrs (0.016÷0.091);(0.071÷0.4);(0.138÷0.78);(0.32÷1.8)/6 hrs
600	(3.2÷17)e-003	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-008	(25÷132)÷ (109÷580);(212÷1128);(491÷2610)/1 month
700	(3.2÷17)e-004	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-009	(2.5÷13.2);(11.0÷57.9);(21.2÷112.8);(49.1÷261)/1 month
800	(3.2÷17)e-005	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-010	(0.248÷1.32);(1.1÷5.8);(2.1÷11.3);(4.91÷26.1)/1 month
900	(3.2÷17)e-006	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-011	(0.025÷0.132);(0.11÷0.58);(0.212÷1.13);(0.49÷2.6)/1 month
1000	(3.2÷17)e-007	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-012	(0.003÷0.013);(0.01÷0.06);(0.02÷0.113);(0.05÷0.26)/1 month
1100	(3.2÷17)e-008	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-013	(0.036÷0.2);(0.157÷0.83);(0.306÷1.62);(0.71÷0.376)/1 year
1200	(3.2÷17)e-009	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-014	(0.004÷0.02);(0.016÷0.08);(0.03÷0.162);(0.07÷0.38)/1 year
1300	(3.2÷17)e-010	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-015	...
1400	(3.2÷17)e-011	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-016	*For next heights the drift distance is less*
1500	(3.2÷17)e-012	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-017	
1600	(3.2÷17)e-013	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-018	
1700	(3.2÷17)e-014	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-019	
1800	(3.2÷17)e-015	((0.74÷3.9);(3.2÷17.3);(6.32÷33.6);(14.6÷77.7))e-020	

V. CONCLUSIONS

Given research results on nano-accelerometer development for measurement of accelerations of the objects moving in the rarefied layers of the upper layer of the Earth atmosphere in the altitude range up to 1000 km confirm the effectiveness of their application in control systems of the objects, functioning for a long time in the given orbits. Acceleration measured by nano-accelerometer will be used for correction of object motion in the given orbit under any changes of perturbing factors.

Nano-accelerometers of this class can be used in control systems of the space objects, whose motion orbits can be located at larger distances from the Earth. An electric solar sail can be used as such an object [12]. Its functioning specifics pertain to the fact that solar radiation can be used as the main force initiating its motion in the given orbit. This force is able to move a sail of 200 kg weight with acceleration of 1 millimeter/sec2, and within one year its speed in the orbit reaches the value of 30km/second. The development of nano-accelerometer algorithms for the electric solar sail is a real challenge.

When a solar sail moves, solar radiation acts as the main perturbation factor.

Thus, first of all, analogues of rarefied layers of the upper atmosphere in the altitude range up to 1000 km and also analogues of environments for altitudes over 1000 km, where the light pressure is the main perturbation factor, have been considered as the rarefied environments resisting the object motion. Respectively, in the first case we have taken the coefficients of aerodynamic forces for the coefficients of resistance against object motion in the rarefied environments, and in the second – light pressure force coefficients.

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Aleksandrs Matvejevs, Andrejs Matvejevs. Cieta ķermeņa nanopaātrinājuma mērīšana retinātā atmosfērā
Rakstā tiek apskatīta cieta ķermeņa, kas kustas retinātā gāzē, nanopaārtinājuma problēmas risināšana. Par retināto vidi, kas pretojas objekta kustībai, pieņem Zemes augšējo retināto slāņu analogu augstuma diapazonā no 1500 km un augstāk. Par pētījuma galvenajiem objektiem, uz kuriem orientēta izstrādāto metožu sistēma, tiek ņemti dažādu mērķu kosmiskie aparāti. Šīs problēmas atrisināšanai izmanto principiāli jaunu metodi, kā noteikt objekta kustības retinātā gāzē paātrinājumu. Pamatā ir kinemātiski saistītu cietu ķermeņu, kas pārvietojas retinātā gāzē un atšķiras ar masu, „zelta" šķēluma laukumu un pretestības koeficientiem savstarpējās iedarbības princips. Turklāt, vispārīgā gadījumā var būt ļoti dažādi cieto ķermeņu savstarpējās iedarbības varianti. Rakstā sniegts īss tāda algoritma matemātiskais pamatojums, ar kuru var noteikt objekta, kas atrodas retinātā gāzē, paātrinājumu. Veikta nanoakselerometra algoritma izpēte objektam no diviem cietiem ķermeņiem, kad objekta masa ir nemainīga vai mainās nejaušos laika momentos. Iegūti pētāmā objekta, kas atrodas retinātā gāzē ārējo spēku iedarbībā, kustības orbītas izmaiņu raksturlielumi, kas atkarīgi no laika intervāla starp orbītas automātiskās korekcijas režīmiem. Modelējot ar dotās klases nanoakselerometru pētāmā objekta funkcionēšanas īpatnības, tika izmantotas MatLab funkcijas un Simulink. Pētīšanas rezultāti apstiprina dotās klases nanoakselerometru izmantošanas efektivitāti reāliem objektiem, kas funkcionē retinātā gāzē. Ar nanoakselerometru noteiktie paātrinājumi tiks izmantoti objekta kustības korekcijai dotajā orbītā pie jebkādiem izmaiņas veidojošiem faktoriem. Šīs klases nanoakselerometri var izmantot kosmosa aparātu, kuru kustību orbītas atrodas lielā attālumā no Zemes, vadības sistēmās. Tāds aparāts varētu būt elektriskā saules bura, kuras kustību pa doto orbītu galvenokārt nodrošina saules radiācija.

Александр Матвеев, Андрей Матвеев. Нано-акселерометры для измерения ускорений при движении объектов в разреженных газовых средах
В статье рассматривается решение проблемы определения нано-ускорения движения твёрдого тела в разреженной газовой среде. При этом в качестве разреженных сред, оказывающих сопротивление движению объектов, рассматриваются аналоги разреженных слоёв верхней атмосферы Земли в диапазоне высот до 1500 км и более, а в качестве основных объектов исследования, на которые ориентирована система разработанных методов, выступают космические аппараты различного целевого назначения. Для решения данной проблемы используется принципиально новый способ определения ускорения движения объектов в разреженных газовых средах. В его основе лежит принцип эффекта взаимодействия кинематически связанных твёрдых тел, движущихся в разреженной газовой среде и отличающихся между собой массой, площадью миделевого сечения и коэффициентами лобового сопротивления этой среде. При этом, в общем случае, возможны самые разнообразные варианты взаимодействия твёрдых тел в разреженной газовой среде. В статье дано краткое математическое обоснование алгоритмов определения ускорения движения объектов в разреженной газовой среде. Проведено исследование алгоритма нано-акселерометра для объекта с двумя твердыми телами для случаев, когда масса исследуемого тела постоянна или изменяется случайно во времени. Получены характеристики изменения орбиты исследуемого тела под воздействием внешних сил в разреженной газовой среде в зависимости от интервала времени между режимами автоматической коррекции орбит. Моделирование особенностей функционирования исследуемого объекта с нано-акселерометром данного класса проводилось с применением функций МАТЛАВ и Симулинк. Результаты исследований подтверждают эффективность использования нано-акселерометров данного класса для реальных объектов, функционирующих в разреженной газовой среде. Измеренное нано-акселерометром ускорение будет использоваться для коррекции движения объекта на заданной орбите при любых изменениях возмущающих факторов. Нано-акселерометры данного класса могут найти применение в системах управления космических объектов, орбиты движения которых могут находиться на больших расстояниях от Земли. В качестве такого объекта может выступать электрический солнечный парус. Особенность функционирования такого солнечного паруса заключается в том, что основной силой, обеспечивающей его движение на заданной орбите, является солнечная радиация.