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Balloon payload attitude control system

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1. Introduction

Balloons are common used in scientific research including, even, perspective study of other planets. Native researchers have realized a mission in the Venus atmosphere during which the balloon remained in the atmosphere for several days. The Soviet interplanetary "Vega-1" and "Vega-2" spacecraft let out a pair of such devices with on-board instruments in 1985.

The NASA (JPL) specialists test the balloons covered with dense layer of thin aluminium and teflon enable to protect them during floating in acrid clouds of sulphuric acid. NASA will study the Venus in the framework of new large-scale mission to the planet. The mission is to be started soon after the new satellite will have been launched to Jupiter and its moons in 2020 [1]. A pair of sondes is to be fastened at the balloons floating in the Venus atmosphere at altitude about 55 km. It is proposed that the new balloons will remain for several months and bend around the planet not less than seven times [2].

Lately the balloons experiments have been used with educational purpose as well. The striking example is the BEXUS European educational program [2]. Within the program the experience of devices, payload and autonomous control systems creation is gained and the experiment realization skills are developed. The experiment aims can be various but there are specific tasks where the payload attitude and instrument pointing to given regions of the underlying Earth surface are important. At the same time a system of attitude determination and control can be independent research object, for example, for development of perspective spacecraft units.

Usually, flywheels are common used for such objects as actuators for attitude control systems [4], [5]. Though these systems are rather accurate and reliable, they come to considerable cost. In the paper to use a ventilated engine as the attitude control system actuator is proposed. The engine is a ventilator fit at the motor axis and fixed away from the centre of mass for control torque development. They are easy-to-develop and simple to operate, rather low-cost and, at the same time, they are not less effective than flywheels at low altitudes (specific altitudes depend on motor parameters).

Ventilated engines can be used both as a system for attitude control and for a spacecraft jets imitation. The paper deals with the attitude control system developing which uses these engines as actuator.

2. Project EXUS

Project EXUS (EXperiments for University Students) is a unique opportunity for students to design, develop, build and fly their own experiments in subspace conditions with a stratospheric balloon launched from the Esrange Space Center. Students from the Eramsus Mundus Master Course in Space Science and Technology – SpaceMaster , 120 ECTS and Civil Engineering Program, at the Department of Space Science, Luleå University of Technology in Kiruna, Sweden are involved in the project. It is the students themselves who lead, design and build the instruments on the basis of their respective areas of competence.

The balloon has 1500 m^3 total volume, 4 kg payload capacity, 35 km maximum altitude. This gives the students a challenging environment, i.e. temperature is about 70º C, 1% of the air pressure at sea level, for testing the experiments. The experiment consists of the following steps:

- Start with a scientific idea. Make a theoretical analysis of the project, what is expected, how to analyze the results etc.
- Make a survey of the technical aspects of the project, limitations of the experiment, weight, size, probes etc.
- Write a proposal for the completed project.
- If the proposal is approved design and building phases start. Students contact with staff at the Esrange Space Center on a technical matter.

Normal requested ascend speed is 5 m/s with an estimated time of 1 hour and 40 min to float level at 29 km altitude. Cut down normally is executed after clearance from the instrument project manager and based on calculations for a safe landing, i.e. 4-5 hours after the launch in Sweden or in Finland.

BEXUS belongs to Esrange, DLR and ESA (students participate if they win the competition, so it is their area of interest and is a sensitive matter).

The balloon has a total volume of 10.000 cubic meters and grows to a diameter of 40 meters when the maximum altitude is reached. It has a capacity to carry about 100 kg of payload to an altitude of 30 km.

Fig.1. Launch of EXUS at the Esrange Space Center, Swedish Space Corporation, 2008. Students from the Eramsus Mundus Master Course in Space Science and Technology – SpaceMaster and Civil Engineering Program, Department of Space Science, Luleå University of Technology, Kiruna, Sweden (courtesy of EXUS team)

3. Task setting

Let us consider a rigid body suspended by a string (Fig. 2). It can execute a rotational motion only, so we study the body angular motion around its vertical axis. The ventilated engines are used as actuators for attitude control as stated in the Introduction. Measuring elements are a fiber-optic sensor of angular velocity and a set of photodiodes for attitude determination as position sensors. The main purpose of the attitude control system is damping and turn in a given angle around vertical.

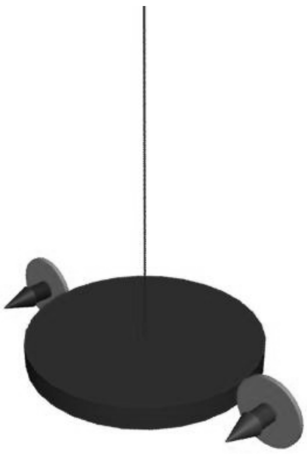

Fig. 2. The control system lay-out

4. Body angular motion equation

Obtain a torque the ventilated engines create. The force *F* generated by engines is determined by formula

$$F = S\Delta p$$

where S is a disk area, Δp is a difference in air pressure before engine passing and after. Using the Bernoulli's equation we can obtain both the pressures

$$p_1 = p_0 + \frac{1}{2}\rho V^2,\ p_2 = p_0 + \frac{1}{2}\rho V_e^2 .$$

Here p_1 is a pressure before passing, p_2 is a pressure after passing, p_0 is a static pressure, V_e is an air flow velocity after passing, V is an approach flow velocity (consider $V_e > V$). Then, the force is

$$F = \frac{1}{2} S\rho (V_e^2 - V^2) .$$

Thus, torque is as following

$$M = \frac{1}{2} RS\rho (V_e^2 - V^2)$$

where R is the distance between rotation axis and engine. Spin rotation equation of such a system is written as follows

$$J\dot{\omega} + \delta\omega + \gamma\alpha = \frac{1}{2}\rho SR(V_e^2 - V^2) . \qquad (1)$$

Here J is a body moment of inertia about spin axis, δ is a coefficient of resistance, γ is a coefficient of elasticity of the string, ρ is air density, S is a disk area covered by the spinning ventilator, R is a distance between the axis of the body rotation and the ventilator, V_e is a velocity of air flow leaving the spinning ventilator (it is one of the engine parameters and do not change when the engine is working), V is a velocity of air entering the ventilator, the dot stands for differentiation operation with respect to time *t*. It is clear that $V = \omega R$, so write the (1) equation as

$$\dot{\omega} + \frac{\delta}{J}\omega + \frac{1}{2}\frac{\rho SR^3}{J}\omega^2 + \frac{\gamma}{J}\alpha = \frac{1}{2}\frac{\rho SRV_e^2}{J} . \qquad (2)$$

Come to dimensionless angular velocity and time by formulas $\omega = {}^{V_e}\!/_{R}\,\Omega,\ t = {}^{R}\!/_{V_e}\,\tau$.

Substituting these expressions in the (2) derive the equation

$$\frac{d\Omega}{d\tau}+\frac{\delta}{J}\frac{R}{V_e}\Omega+\frac{1}{2}\frac{\rho SR^3}{J}\Omega^2+\frac{\gamma}{J}\frac{R^2}{V_e^2}\alpha=\frac{1}{2}\frac{\rho SR^3}{J}.$$

Introduce following dimensionless parameters

$$k=\frac{1}{2}\frac{\rho SR^3}{J},\ \varepsilon_1=\frac{\delta}{J}\frac{R}{V_e},\ \varepsilon_2=\frac{\gamma}{J}\frac{R^2}{V_e^2}.$$

Then the equation (2) is to be rewritten as following

$$\Omega'+\varepsilon_1\Omega+k(\Omega^2-1)+\varepsilon_2\alpha=0. \qquad (3)$$

Let us study this equation.

5. Study of the system torsional motion

Write a solution of the equation (3) under the assumption $k>>\varepsilon_1,\varepsilon_2$ assuming $\varepsilon_1=\varepsilon_2=0$. Then it has a form

$$\Omega'=k-k\Omega^2 \qquad (4)$$

and its solution is written as follows:

$$\Omega=\frac{1-\tilde{C}\exp(2k\tau)}{1+\tilde{C}\exp(2k\tau)}.$$

Rewrite this solution using dimensional variables

$$\omega=\frac{V_e}{R}\frac{1-C\exp(2k\frac{V_e}{R}t)}{1+C\exp(2k\frac{V_e}{R}t)}. \qquad (5)$$

Here a notation $C=\frac{V_e-\omega_0 R}{V_e+\omega_0 R}$ is introduced. When density depends on time, that is, $k(t)=SR^3\rho(t)/2J$ the solution of the equation (4) can be written as

$$\omega=\frac{V_e}{R}\frac{1-C\exp(\frac{SR^2V_e}{J}\int_0^t\rho(t')dt')}{1+C\exp(\frac{SR^2V_e}{J}\int_0^t\rho(t')dt')}. \qquad (5a)$$

If introduce the following notations in the expression (5)

$$A=\frac{V_e}{R},\ B=k\frac{V_e}{R},$$

then (5) is written as

$$\omega = A\frac{1 - C\exp(2Bt)}{1 + C\exp(2Bt)}. \tag{6}$$

The solution of the equation (3) for the angular velocity and rotation angle within free-running damped vibration is equal to (the ventilator is switched off, so $k(\Omega^2 - 1) = 0$)

$$\alpha = \alpha_0 \exp(-\frac{\varepsilon_1}{2}\tau)\cos(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\tau) + \frac{\Omega_0 + \frac{\varepsilon_1}{2}\alpha_0}{\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}}\exp(-\frac{\varepsilon_1}{2}\tau)\sin(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\tau),$$

$$\Omega = -\frac{\alpha_0\varepsilon_2 + \frac{\varepsilon_1}{2}\Omega_0}{\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}}\exp(-\frac{\varepsilon_1}{2}\tau)\sin(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\tau) + \Omega_0 \exp(-\frac{\varepsilon_1}{2}\tau)\sin(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\tau).$$

Coming back to dimensional velocity we derive

$$\omega = -\frac{\alpha_0 \frac{V_e}{R}\varepsilon_2 + \frac{\varepsilon_1}{2}\omega_0}{\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}}\exp(-\frac{\varepsilon_1}{2}\frac{V_e}{R}t)\sin(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\frac{V_e}{R}t) + \\ + \omega_0 \exp(-\frac{\varepsilon_1}{2}\frac{V_e}{R}t)\sin(\sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\frac{V_e}{R}t). \tag{7}$$

Introduce the following notations

$$\theta = \sqrt{\varepsilon_2 - \frac{\varepsilon_1^2}{4}}\frac{V_e}{R},\ \Delta = \varepsilon_1 \frac{V_e}{R}.$$

Reverse transfer is realized by formulas

$$\varepsilon_1 = \Delta\frac{R}{V_e},\ \varepsilon_2 = \frac{R^2}{V_e^2}(\theta^2 + \frac{\Delta^2}{4}).$$

The expression (7) becomes by new notations as follows

$$\omega = -\frac{(\theta^2 + \frac{\Delta^2}{4})\alpha_0 + \frac{\Delta}{2}\omega_0}{\theta}\exp(-\frac{\Delta}{2}t)\sin(\theta t) + \omega_0 \exp(-\frac{\Delta}{2}t)\sin(\theta t). \tag{8}$$

This expression provides a relation between the angular velocity and damped vibration parameters which can be presumably determined, for example, by least-mean-square method.

6. The body angular motion control

Integrate the expression (6) assuming $\omega = d\alpha/dt$,

$$\alpha = At - \frac{A}{B}\ln\frac{1 + C\exp(2Bt)}{1 + C} + \alpha_0 . \tag{9}$$

Extract time from (6) and substitute in (9) we obtain

$$\alpha = \frac{A}{2B}\ln\frac{A^2 - \omega^2}{A^2 - \omega_0^2} + \alpha_0 . \tag{10}$$

The expression (10) gives two families of curves on the phase plane (α, ω): for positive rotation ($A > 0$) and for negative one ($A < 0$). Consider the task in two settings:

1. The body rotates with a certain angular velocity, it is necessary to stop the rotation.
2. The body occupies an angular position, it is necessary to turn it in a certain angle.

With respect to response-time problem both tasks are a transfer from one point at the phase plane to another one. The Fig. 3 illustrates the second task which it realizes the transfer from point 1 to point 2.

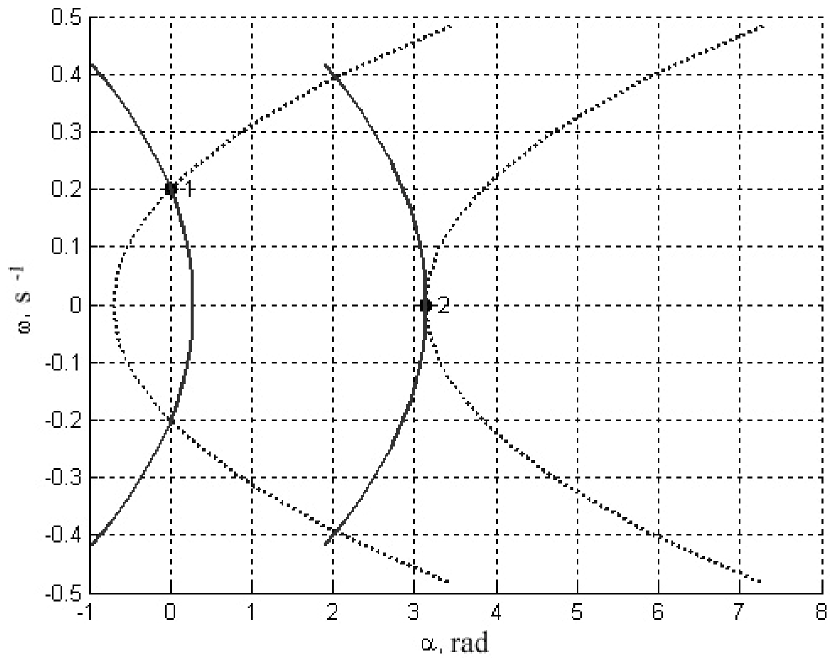

Fig. 3. The task of rotation in a given angle (i.e. a transfer from point 1 to point 2)

First, the motion track takes place along the dotted curve from point 1 to the point of crossing with a firm line and then down along the firm line to the point 2. It means that, at first, one ventilator works and when a certain angular velocity value is reached, switching happens, the first engine is shut down and the second one turns on. The second motor is shut down after zero speed reach. Define a switching moment of time. Write the expression (10) for the points (1) and (2) consequently

$$\alpha = \frac{A_1}{2B_1}\ln\frac{A_1^2-\omega^2}{A_1^2-\omega_1^2}+\alpha_1,$$
$$\alpha = \frac{A_2}{2B_2}\ln\frac{A_2^2-\omega^2}{A_2^2-\omega_2^2}+\alpha_2. \tag{11}$$

Here (α_1, ω_1) is an initial state and (α_2, ω_2) is a final one.

In the rotation task $\alpha_1 = 0, \omega_2 = 0$, so derive the equation for the switching moment of time definition using (11),

$$\frac{A_1}{2B_1}\ln\frac{A_1^2-\omega^2}{A_1^2-\omega_1^2} = \frac{A_2}{2B_2}\ln\frac{A_2^2-\omega^2}{A_2^2}+\alpha_2. \tag{12}$$

Generally, one failes to solve this equation in the completed form but when the engines are identical, that is, $A_1 = -A_2 = A,\ B_1 = B_2 = B$, the equation (12) becomes

$$\frac{A}{B}\ln\frac{A^2-\omega^2}{A\sqrt{A^2-\omega_1^2}} = \alpha_2.$$

From this we determine the switching conditions

$$\textit{if}\ \ \alpha_2 > 0,\ \textit{then}\ \ \omega = A\sqrt{1-\sqrt{1-\left(\frac{\omega_1}{A}\right)^2}\exp(\frac{B\alpha_2}{A})},$$
$$\textit{if}\ \ \alpha_2 < 0,\ \textit{then}\ \ \omega = -A\sqrt{1-\sqrt{1-\left(\frac{\omega_1}{A}\right)^2}\exp(\frac{B\alpha_2}{A})}.$$

Let us describe algorithm which can be used at the on-board computer for the ventilators control. The switching function is described by a following dotted curve on the phase plane (the curve appearance is shown in Fig. 4):

$$f(\alpha,\omega) = \begin{cases} \alpha - \dfrac{A_2}{2B_2}\ln\dfrac{A_2^2-\omega^2}{A_2^2}, \alpha \le 0, \\ \alpha - \dfrac{A_1}{2B_1}\ln\dfrac{A_1^2-\omega^2}{A_1^2}, \alpha > 0. \end{cases} \tag{13}$$

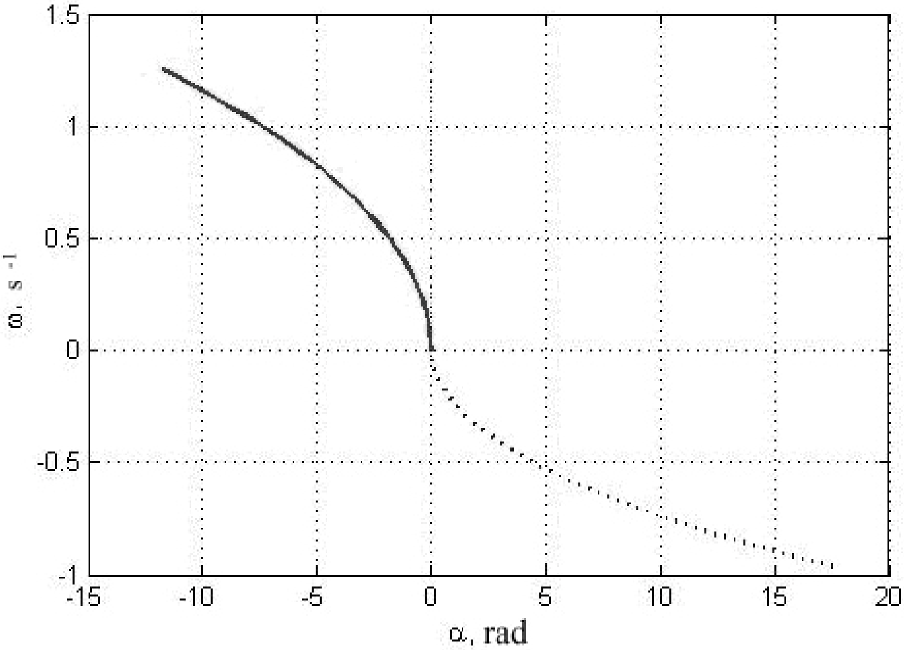

Fig. 4. The switching curve

The control algorithm works in the following way:

1. The initial phase state (α_0, ω_0) determination takes place, at that the switching curve branch is determined:

$$\alpha_0 \le 0 \Rightarrow f = \alpha - \frac{A_2}{2B_2}\ln\frac{A_2^2 - \omega^2}{A_2^2},$$

$$\alpha_0 > 0 \Rightarrow f = \alpha - \frac{A_1}{2B_1}\ln\frac{A_1^2 - \omega^2}{A_1^2}.$$

   If the required value of the rotation $\Delta\alpha$ is given, then

$$\Delta\alpha \ge 0 \Rightarrow f = \alpha - \frac{A_2}{2B_2}\ln\frac{A_2^2 - \omega^2}{A_2^2},$$

$$\Delta\alpha < 0 \Rightarrow f = \alpha - \frac{A_1}{2B_1}\ln\frac{A_1^2 - \omega^2}{A_1^2}.$$

2. The function $f(\alpha_0, \omega_0)$ is calculated. If $f(\alpha_0, \omega_0) > 0 \Rightarrow$ the ventilator with A_2, B_2 works. If $f(\alpha_0, \omega_0) < 0 \Rightarrow$ the ventilator works with A_1, B_1.
3. The measuring of (α, ω) or calculation of values measured are realized and expression $\Delta = |f(\alpha, \omega)| - \sigma_1$ sign is defined, here σ_1 is an allowable deviation from the calculated curve.

4. The motion along the switching curve takes place. At the same time the verification of $|\omega| < \omega_1$ is carried out. Here ω_1 is a precision of the angular velocity determination. If verification is successful, i.e. the angular velocity small value is reached then verification of $|f(\alpha, \omega)| < \alpha_1$ is executed. Here α_1 is an angular accuracy. If this verification is successful, it means that the system has approached the required state; if it is not, the items 1-4 should be repeated.

It should be remarked that another switching scheme is possible too. First, one calculates the functioning time of the first ventilator and, then, the functioning time of the second one. In this case two time moments, the switching time and the second ventilator shutting down time, are calculated at the angular velocity and/or the switching angle information sampling. Both of these methods are equivalent with respect to time-response.

7. The air density change during ascent

During the balloon ascent the air density decreases which influences the engine force and, therefore, the angular velocity evolution character during the control phase (5a). Show that in this case the task is complicated but not greatly. Derive the dependence of the air density w.r.t. time.

Use the barometric formula for definition of dependence of the air density and pressure with respect t altitude

$$P = P_0 e^{-\frac{\mu g}{RT} z}, \; \rho = \rho_0 e^{-\frac{\mu g}{RT} z}. \tag{14}$$

These formulas are derived for a constant temperature case. Deduce these formulas for the case when the temperature depends on the altitude. One knows following approximations for altitude change [6]:

$T = T_1 + \alpha_1 z$ at altitude change from 0 km to 11 km,

$T = T_2$ at altitude change from 11 km to 20 km,

$T = T_3 + \alpha_3 z$ at altitude change from 20 km to 32 km.

Here $T_1 = 288.15 K$, $T_2 = 216.65\ K$, $T_3 = 288.65\ K$, $\alpha_1 = -6.5 K/km$, $\alpha_3 = 1 K/km$. In case of constant temperature (from 11 to 20 km altitude) the density and pressure dependences take the form of the barometric formula. Now derive this dependence at

$T = T_0 + \alpha z$ (instead of this one can use the results [7] which decribe the density-altitude dependence). It has the form

$$P = P_0(1+\frac{\alpha}{T_0}z)^{-\frac{\mu g}{R\alpha}}, \rho = \rho_0(1+\frac{\alpha}{T_0}z)^{-\frac{\mu g}{R\alpha}}. \quad (15)$$

To derive the time-density dependence it is necessary to know how the altitude changes in time. Write an equation describing the balloon ascent

$$m\ddot{z} = \rho_в gV - mg. \quad (16)$$

Here $\rho_в$ is the air density, V is the balloon volume. At the ascent both quantities change. The balloon expands to the maximum volume, so that, the pressure inside the balloon equals to the air pressure outside. In order to derive the altitude where the maximal pressure is reached, use the ideal gas equation

$$PV = \nu RT, P_0(1+\frac{\alpha}{T_0}z)^{-\frac{\mu g}{R\alpha}} V_{\max} = \nu RT_0(1+\frac{\alpha}{T_0}z).$$

From these relations the altitude where the volume is maximal is derived according to the formula

$$z_{\max} = \frac{T_0}{\alpha}\left(\left(\frac{P_0 V_{\max}}{\nu RT_0}\right)^{\frac{\alpha R}{\alpha R+\mu g}} - 1\right).$$

The air density can be deduced in the following way:

$$\rho_в = \frac{m}{V} = \frac{\mu_в P_в}{RT},$$

The balloons volume is

$$V = \frac{m_{He}}{\mu_{He}}\frac{RT}{P_{He}}.$$

Till $z_{\max}$ altitude one can consider that $P_в = P_{He}$ then (16) is rewritten in a form

$$m\ddot{z} = g(\frac{\mu_в}{\mu_{He}}m_{He} - m).$$

It means that until the balloon ascends to $z_{\max}$ altitude, it ascends in a uniformly accelerated way. Then the altitude-time dependence has a form

$$\rho = \rho_0(1+\frac{\alpha}{T_0}\frac{g}{m}(\frac{\mu_в}{\mu_{He}}m_{He} - m)\frac{t^2}{2})^{-\frac{\mu g}{R\alpha}}.$$

For the case when the temperature is constant, the solution at non-constant volume has the same form.

Now consider a case when the balloon has reached the maximal volume, that is, $V = V_{\max}$. Use dependences (14), (15) of density with respect to altitude in order to derive the dependences of the air density with respect to altitude. Solve (14), (15) with regard to *z*:

$$z = -\frac{\mu g}{RT_0}\ln\frac{\rho}{\rho_0},\quad z = \frac{T_0}{\alpha}\left(\left(\frac{\rho}{\rho_0}\right)^{-\frac{R\alpha}{\mu g}} - 1\right).$$

From these expressions we evaluate the second derivative $\ddot{z}$ and substituting them into the (16), derive accordingly the equations which describe the dependence of density with respect to time,

$$\ddot{\rho} - \frac{\dot{\rho}^2}{\rho} = \frac{RT}{\mu\rho_0}\left(\frac{m\rho - V_{\max}\rho^2}{m}\right),$$

$$\ddot{\rho} - \left(\frac{R\alpha}{\mu g} + 1\right)\frac{\dot{\rho}^2}{\rho} = \frac{RT_0}{\mu\rho_0}\rho_0\left(\frac{\rho}{\rho_0}\right)^{\frac{R\alpha}{\mu g}+1}\left(\frac{m\rho - V_{\max}\rho^2}{m}\right).$$

Their numerical solution becomes simpler because the balloon initial conditions and parameters are known in advance with certain accuracy, so the dependence of the density with respect to time can be derived with necessary credibility value already before the ascent. In addition, if the balloon release is not the first one, pressure and density profile at the launch site is most likely known. It permits to use the expression (5a) not resorting to numerical integration. Thus, at the given law density change with regard to time the expression (5a) is suitable for the angular velocity evolution derivation at variable density.

8. Laboratory testing

The laboratory tests were executed within accepted assumptions for model correctness confirmation, for the ventilators, string and mock-up parameters determination and for the algorithm verification. They took place in the MIPT “Complex information-mechanical systems control and dynamics” Laboratory [8] in the framework of the Program of educational laboratory training works development [9].

8.1. The mock-up description

Describe briefly the mock-up functioning principle and structure. When the mock-up turns on, the power for all of its sub-systems is fed from accumulator battery by means of voltage transducers located at the supply board. The Windows XP Embedded OS is downloaded from the on-board computer compact-flash disk. Then by the Remote Desktop utility of the test bench control computer the mock-up is communicated with the on-board computer via Wi-Fi. After that one can start to carry out the simulation process. The mock-up is controlled by means of two ventilators. Their functioning principle, as is well known, rests on the linear momentum conservation laws. The mock-up scheme is shown in Fig. 5. The mock-up appearance is demonstrated in Fig. 6.

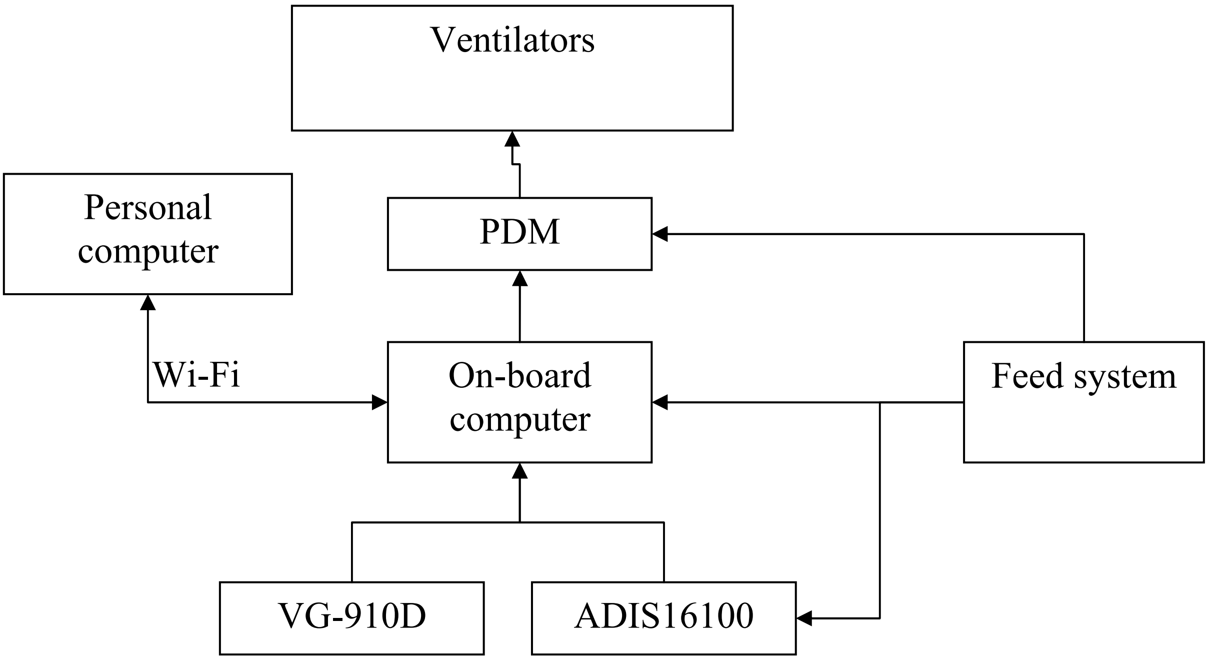

Fig. 5. The mock-up basic circuit

As stated above, the set of several photodiodes is used as the attitude determination sensor. Each photodiod can define an angle between normal to the photodiod plane and direction of the Sun (a graph of current output against the angle is shown in Fig. 7). To exclude uncertainty in the Sun orientation determination it is necessary to use a certain number of sensors and to place them so that two sensors could “see” the Sun at every instant time. Minimum configuration consists of four photodiodes situated at the square sides (Fig. 8). Such configuration is possible only for ideal sensors (their current output has dependence of the angle, as it is shown in Fig. 8). In the areas marked by number #1 the direction of the light source is defined unambiguously (the light source is situated in the two sensors field of vision). The areas #2 are the ones where this direction is defined up to a sign. As the sensor size is small in comparison with light source distance, the areas #1 actually cover all the plane.

The mock-up consists of following sub-systems:

- on-board computer (JRex single-board computer);
- two ventilator engines;
- actuator control system;
- supply board;
- accumulator battery;
- single-axis fiber-optic gyroscopic sensor;
- single-axis angular velocity sensor MEMS
- Wi-Fi adapter.

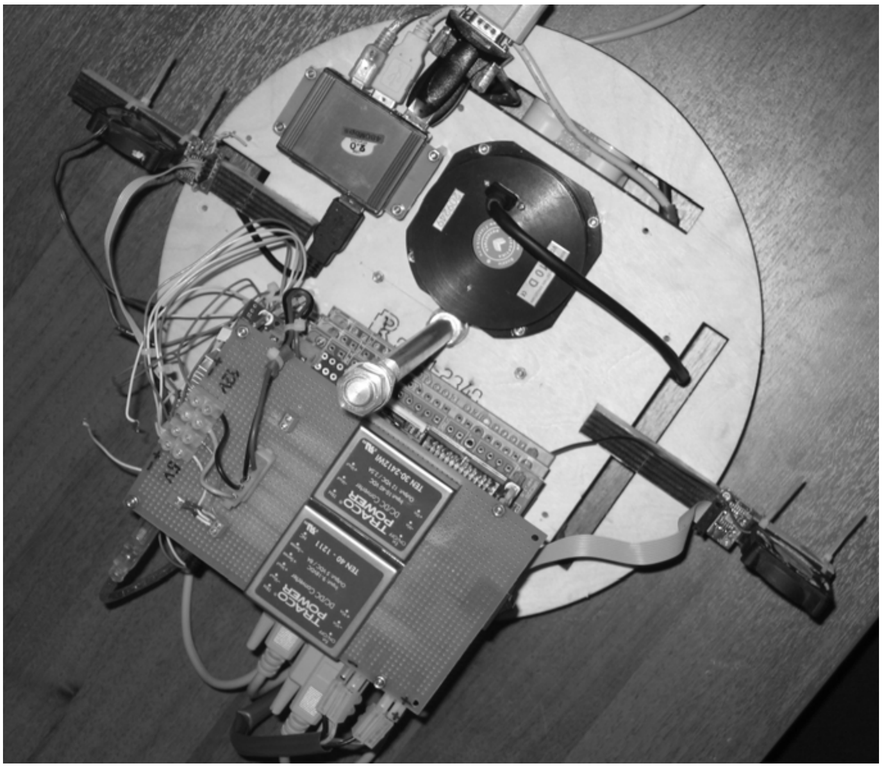

Fig. 6. The mock-up with gyroelements (view from above)

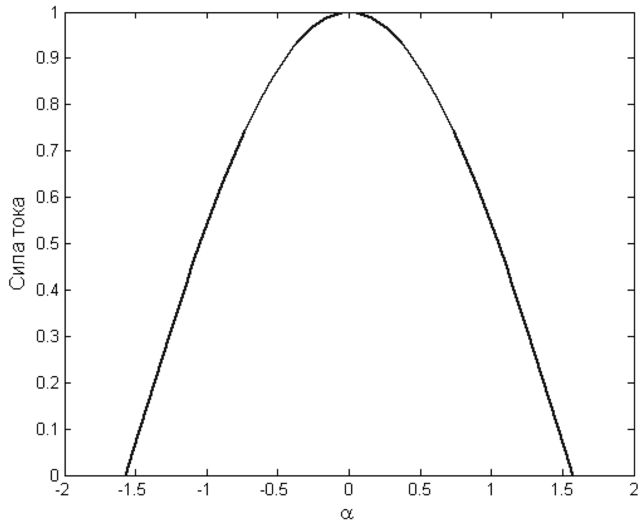

Fig. 7. The dependence of a current output of the sensor with respect to the angle between direction of the Sun and normal to the sensor surface

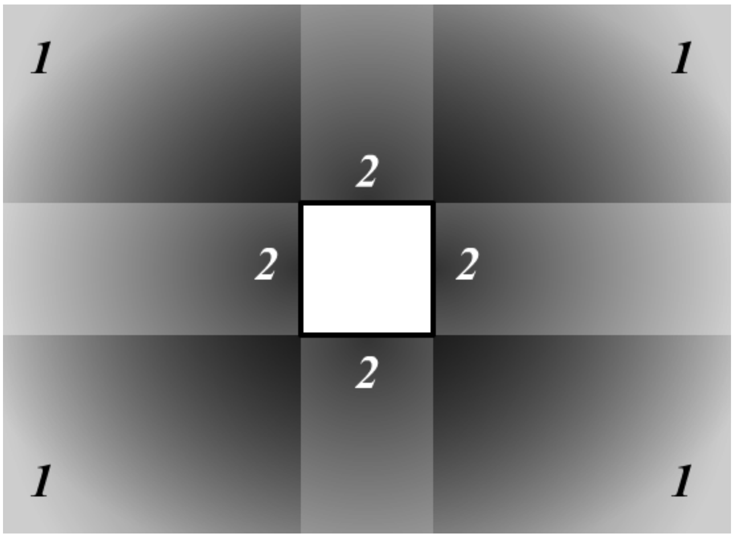

Fig. 8. The sensors layout (black lines at the square sides stand for the sensors, areas #1 stand for the areas where the light source is situated in the two sensors field of vision, areas # 2 are the ones where the light source is situated in the one sensor field of vision)

The mock-up software

The software consists of a routine which works at the mock-up's on-board computer, realizes information read-out and processing the data from the angular velocity sensor, decision making concerning control and results saving to a file. Its flow-block is shown in Fig. 9. The routine is developed in the C++ Builder 6 environment. It works in the following way. A digital signal which is converted in the angular velocity values from the sensor. The angular velocity values of several measurements are summed up, then this sum divided by the measurements amount, so at the output an average value of the angular velocity is derived. Averaging-out is made in order to diminish the influence of the measurement noise and to decrease the routine measurements sampling in a time. The software has an upper limit of output data frequency (≈ 100 Hz). Above this value the routine does not have a time to process the data entering from the sensor and the real-time processing becomes impossible. Therefore, at the routine work parameters setting it is necessary to pay special attention to the averaging. Knowing the data feed frequency one needs to set such averaging (i.e. to choose amount of measurements for averaging) that the routine output data frequency would not exceed a tolerable limit.

Then the averaged angular velocity value enters the Kalman filter inlet based on motion model of the body suspended by a string [9]. At the Kalman filter output a vector of the body state at the phase plane is obtained. Using the information about initial and current body phase state the routine determines a switch curve branch (13) as a result of which the decision about either engine switching on is made. After control is turned on the body starts to rotate under one of the engine control until the phase trajectory reaches the switch curve. Then the backward control turns on, the body begins to brake till it stops. At this time the control turns off. Due to inaccurate control parameter determination, sensors' noise, chance factors the control realization errors are inevitable. So after the control session finishes, a miss calculation is realized by comparison between required state and the current one. If the body is situated out of the permissible vicinity of the given point, miss magnitude is calculated and one more corrective control session takes place. So, the routine developed is actually a closed cycle process which besides can keep the body in the final state in case of external disturbances.

The routine window contains two areas (Fig. 10):

- *Port settings* – working sensors setting, selection of a port which the data enters through, the averaging parameters setting, selection of a port which the engine control is realized through and setting of the body rotation angle value. After the routine parameters setting one can start the calculations process pressing the "Open port" button.
- *Some information* contains information about the sensor input values frequency, about the routine output frequency, depicts the routine work time and one-session received bytes number.

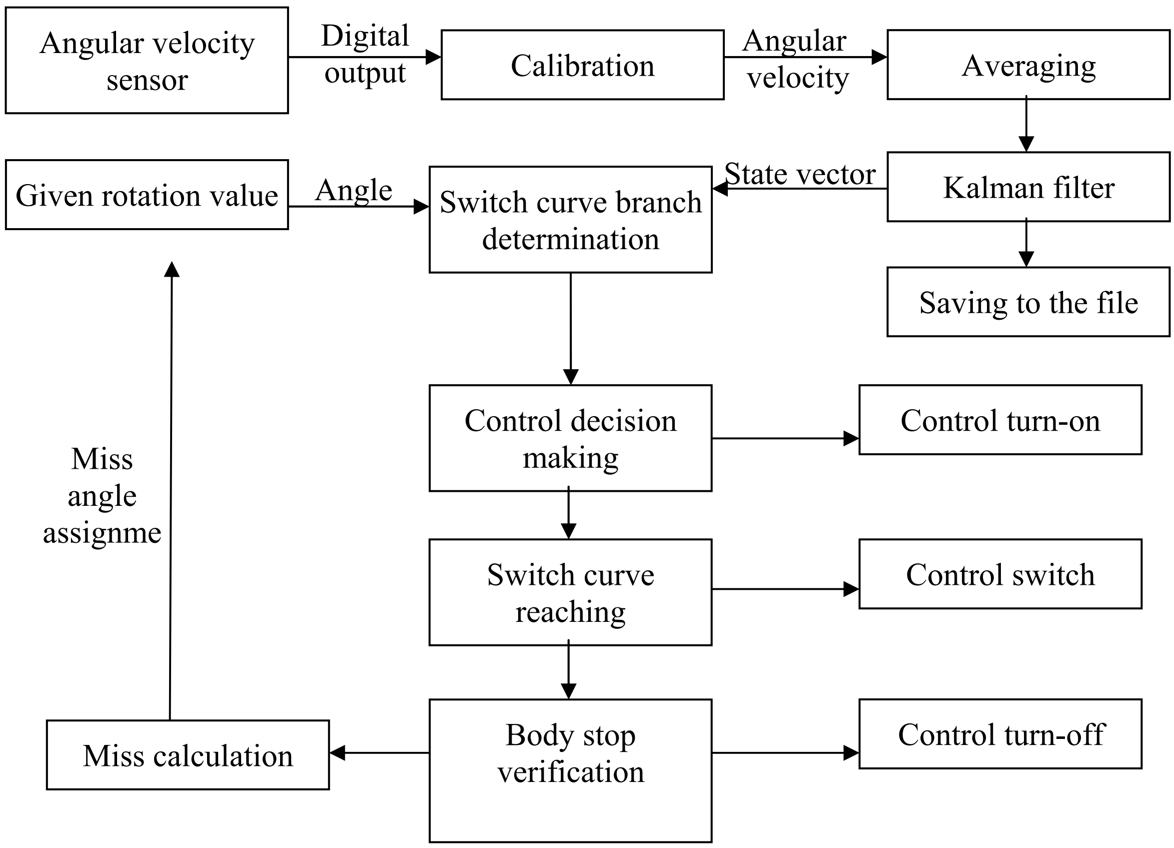

Fig. 9. The routine work scheme

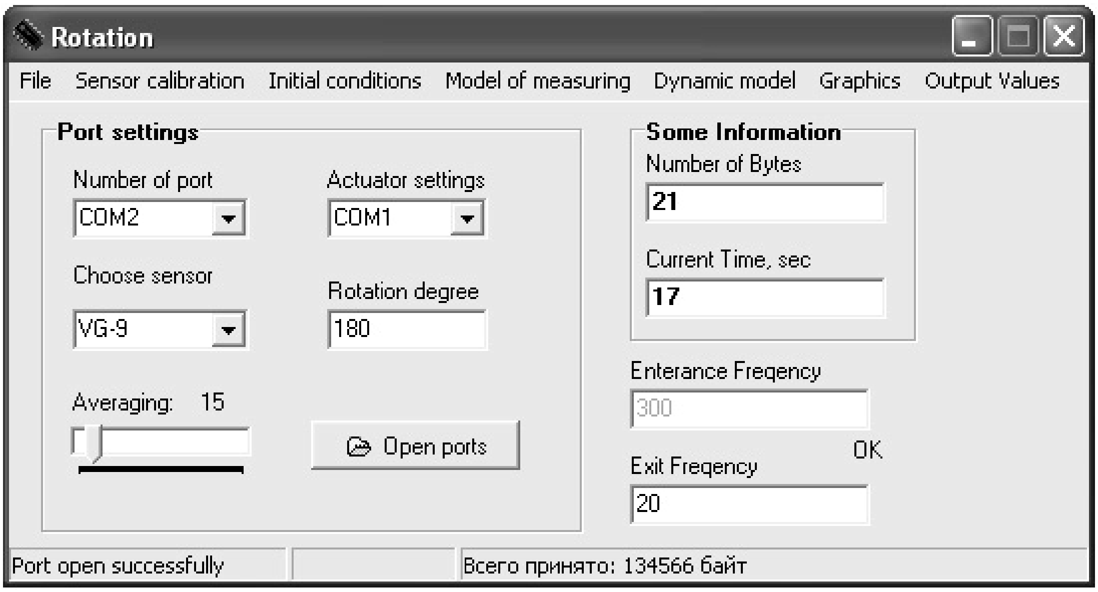

Fig. 10. The routine interface

The main window contains a menu of following issues:

- *File* – program exit.

•*Sensor calibration* – setting of calibration coefficients for the VG-910D and ADIS16100 sensors.

•*Initial conditions* – setting of the mock-up initial state vector.

•*Model of measuring* – setting of the measurement model parameters (of the σ^2 measurements error square and the error matrix elemente values for the Kalman filter).

•*Graphics* – real-time visualization of angular velocity graphs and of deviation angle from the equilibrium position. The graphs depict all the output data of the program.

•*Output values* – demonstration of the mock-up state vector output values on the screen.

8.2. Tests realization methods and their results

8.2.1. The engine parameter determination

As two on-board ventilator motors had different characteristics, their parameter determination was realized independently of one another according to the following plan:

1. The mock-up was set in the rest position.
2. The ventilator engine turning on took place for certain time (~2 min).
3. The initial state $\omega_0 = 0$ was chosen in the (6) motion pattern.
4. The parameters A, B were determined by least-mean square method.

8.2.2. The mock-up and string parameter determination

The parameter determination was realized according to the following plan:

1. The mock-up was turned up to a certain angle.
2. The mock-up was released and the angular velocity calculations run for a period (~20 min) were realized.
3. Crossing of the equilibrium position moment was defined (when the angular velocity is maximum).
4. Values $\alpha_0 = 0, \omega_0 = \omega_{\max}$ were chosen as the initial conditions in the model (8).
5. The parameters θ, Δ were determined by least-mean square method.

Remarks

The values indicated above were chosen as the initial conditions because there were no position sensors on-board at the calibration stage, so the initial spin was known rather approximately in contrast to the angular velocity at crossing of the equilibrium position moment. In the presence of the position sensors one can realize two independent evaluations of the string parameters using various initial conditions ($\alpha_0 = 0, \omega_0 = \omega_{\max}$ и $\alpha_0 = \alpha_{откл}, \omega_0 = 0$).

The laboratory test results are given below. Fig. 11-13 show the results of the tests which were realized for determination of the engine parameters. Fig. 13 illustrates the comparison of the experimental data and the analytical result in case of free oscillations.

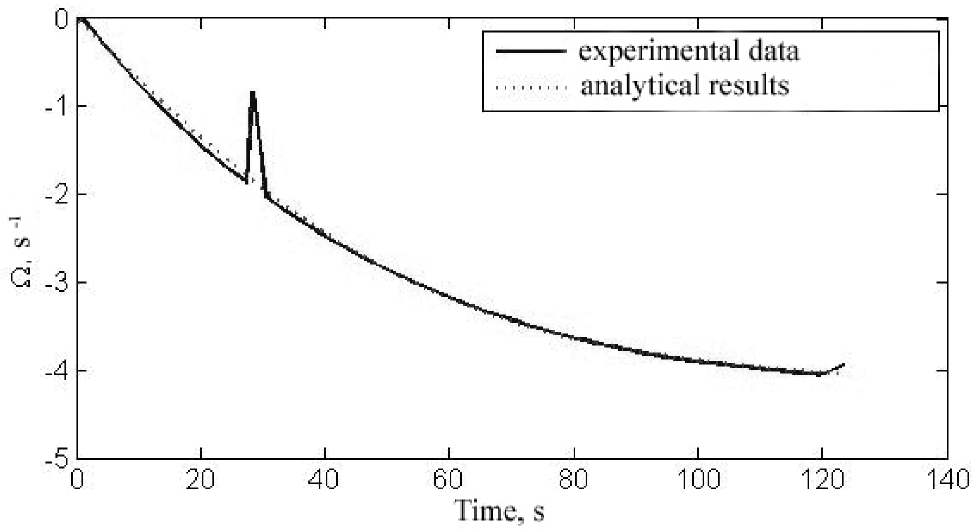

Fig. 11. Experimental and analytical dependences of the angular velocity with respect to time (the analytical curve is plotted using the parameters determined by least-mean square method) with switched-on engine

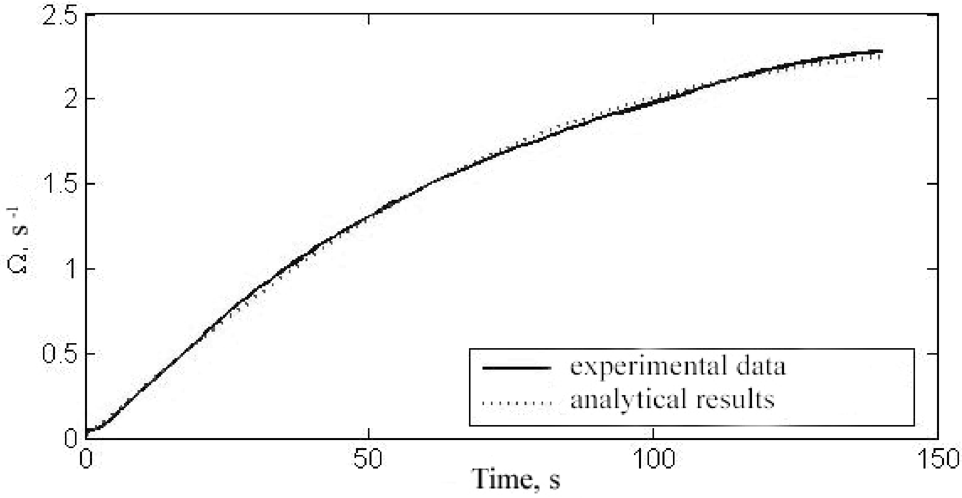

Fig. 12. Experimental and analytical dependences of the angular velocity with respect to time (the analytical curve is plotted using the parameters determined by least-mean square method) with switched-on engine

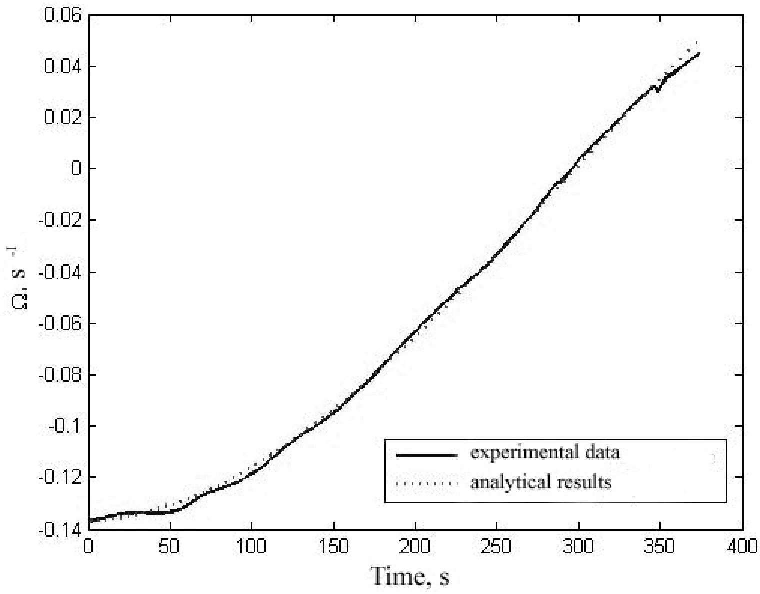

Fig. 13. Experimental dependence of the angular velocity with respect to time and the curve plotted according to (8) using the parameters determined by least-mean square method

While testing the correctness of the assumption $k >> \varepsilon_1, \varepsilon_2$ was verified and the engines' parameters were determined. They turned out to be as follows:

$$A_1 = -2.4157 c^{-1},\ B_1 = 0.0119 c^{-1};$$

$$A_2 = 4.2177 c^{-1},\ B_2 = 0.0168 c^{-1}.$$

Thus, it was determined that while the engines are working it is possible do not take into account the influence of the string which the body is suspended by and also the air resistance.

Consider the proposed algorithm work results. The engine parameters A_1, A_2, B_1, B_2 are defined by the method described above. In Fig. 14 the example of the mock-up turn in $360°$ angle is shown. The dotted line and the thick firm one are theoretical curves, the thin firm line signifies real motion. The Figs. 15-16 show the dependence of the angle with respect to the angular velocity during the turn.

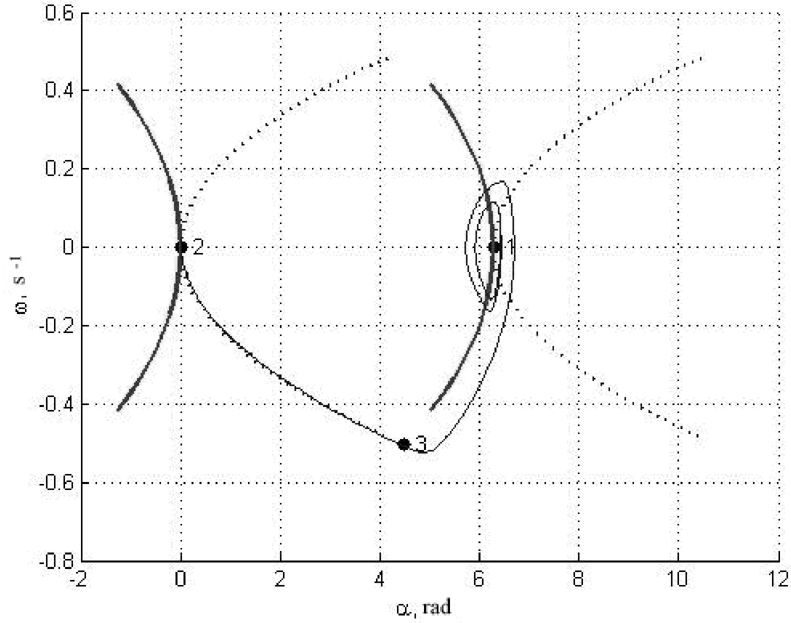

Fig. 14. The phase trajectory at the mock-up turn

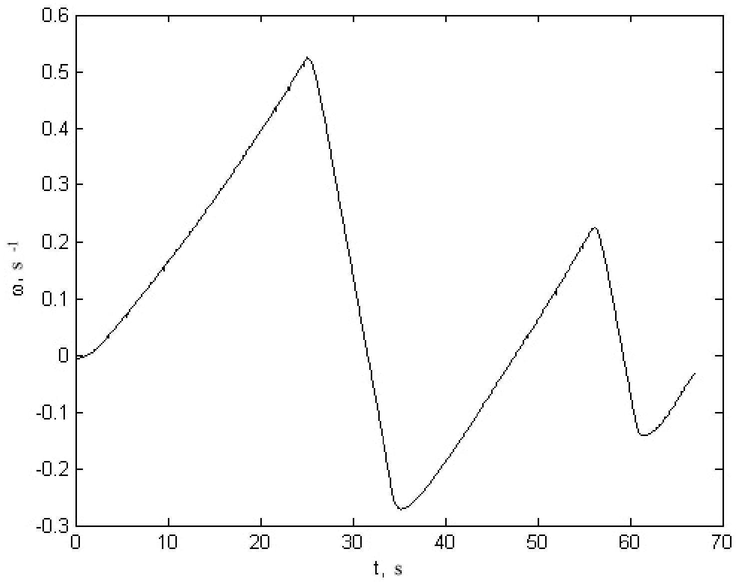

Fig. 15. The dependence of the angular velocity with respect to time

Because of the control errors the trajectory deviates from the given one but the algorithm is plotted so that if the system does not approach the given point the extra iteration is realized.

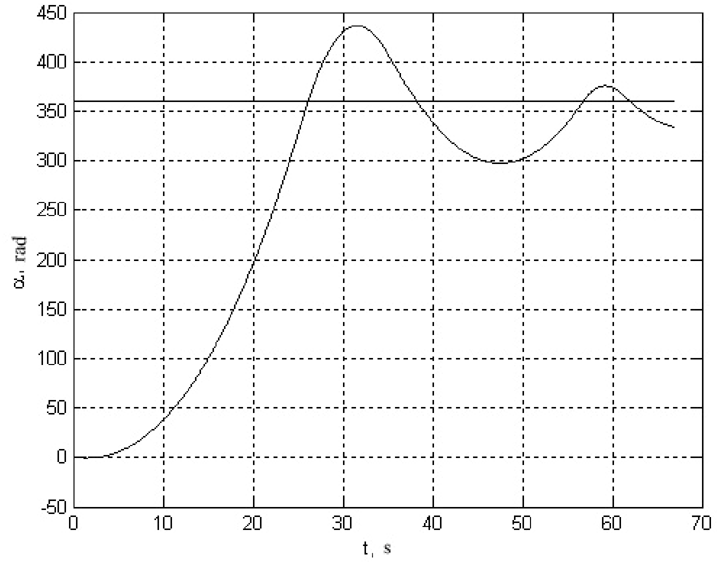

Fig. 16. The angle-time dependence

9. Conclusion

The rather simple for realization but, at the same time (judge by mathematical and laboratory modelling results), effective system of control and balloon payload attitude determination is presented here. The control algorithm and its routine realization are proposed. Also, one has developed and realized the method of the laboratory simulation which was successfully tested in laboratory conditions.

10. Acknowledgements

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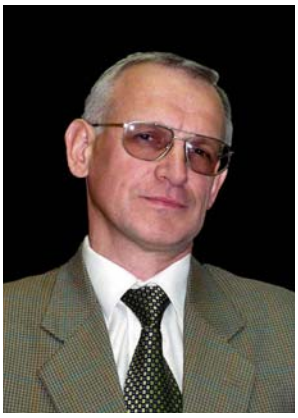

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