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ATTITUDE CONTROL SYSTEM FOR THE FIRST SWEDISH NANOSATELLITE "MUNIN"

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ABSTRACT

The paper describes the passive magnetic attitude control system developed for the Swedish nanosatellite MUNIN, its composition, and the results of the mathematical modeling of the satellite motion around its center of mass under the effects of external torques and control by this attitude control system. The satellite MUNIN is to be oriented along the local vector of intensity of the geomagnetic field. The problems, which are expediently considered hereafter are formulated too.

1. INTRODUCTION

In September 1996, the plans to build and launch a very small satellite were discussed at the Kiruna Division of the Swedish Institute of Space Physics (IRF). The Swedish line of microsatellites had given IRF the inspiration and experience needed to design, together with other participants, a "nanosatellite". From the very beginning the plans were to have a firm scientific goal with the satellite, soon to be named Munin after one of the God Odins ravens.

The scientific objective with MUNIN is to collect data on the auroral activity on both the Northern and Southern hemispheres, such that the data related to the current state of the magntospheric activity can be made available on-line. The data acquired by MUNIN will then serve as an input to the prediction of space weather.

Using modern technology, a very small satellite can be built and still has all necessary functions needed to support a specific scientific mission. The goal of the MUNIN project is both to achieve the scientific objectives and to show that it is possible to achieve them with a very small satellite [1]. The MUNIN satellite of 6 kg weight will have a combined electron and ion spectrometer, an instrument first to be flown on the Swedish Astrid-2 mission. The spectrometer, called Medusa, is built by Southwest Research Institute (SwRI). In addition, the satellite will measure high energy particles with a solid state detector, and image aurora with a miniature CCD-camera. The shape of the satellite is a cube with 21-cm edge. The view of MUNIN's engineering model is shown in Fig.1. Silicon solar arrays cover all sides of the cube and a Li-Ion battery provides the needed power. The satellite uses the UHF-band for the up- and downlink to the ground station located at the Institute in Kiruna. Digital Signal Processors perform instrument control, data compression and telemetry formatting, as well as serving as a software modem. The launch of MUNIN satellite into orbit is planned on 21st of October, 1999 by Delta-2 rocket as a secondary

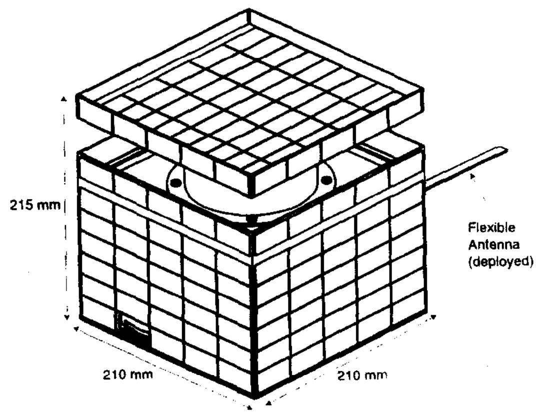

Figure 1: The draft of nanosatellite MUNIN

payload.

The activity of the Attitude Control System & Orientation Division at the Keldysh Institute of Applied Mathematics RAS [2] in area of ACS for small satellites gave the appropriate opportunity to propose the attitude control system for the MUNIN satellite. After the preliminary evoluation of the satellite dynamics with the passive magnetic attitude control system composed a strong permanent magnet and hystersis rods as a damper, it was decided to provide the satellite with this kind of system.

There are mythological circumstances concering MUNIN. The name of the satellite comes from Nordic mythology: "The ravens Munin and Hugin flew out and brought back news from every corner of the world. Sitting on the God Odin's shoulders, they whispered all the news in his ears. Munin represented the memory and Hugin the intelligence... and they were his embodied soul..."

2. CHOICE OF MAGNETIC ATTITUDE CONTROL SYSTEM TYPE

The satellite does not require the high precision of orientation and executing the complex rotation programme during the flight, and opportunities of the actuators and orientation sensors installation alongside with computer and supply of energy are away. The deviation from the Earth's magnetic field vector local intensity $\mathbf{H}$ should not exceed $10 \div 15°$ during all time of the active flight, allowable time of the transient motion should not exceed 2 – 3 weeks. The system should not contain moving elements, consume the power-generating and information resources of satellite. At last, this system must be to the utmost cheap one. Therefore, the problem of the attitude control system type choice is unequivocal decided for the benefit of the passive magnetic system. For the considered nanosatellite all these conditions are valid. Let us consider the composition of such attitude control system.

3. COMPOSITION OF PASSIVE MAGNETIC ATTITUDE CONTROL SYSTEM

At the elaboration of the passive magnetic system, ensuring orientation along vector $\mathbf{H}$, it is necessary to solve two basic problems concerning the development of both restoring and damping torques. The problem of restoring torque development is solved by a strong permanent magnet. From the ways available to solve the problem of initial angular motion energy dissipation, the damping device composed of hysteresis rods, which are manufactured from a soft-magnetic material and re-magnetized in geomagnetic field under satellite rotation relative to a force line of this field, can generate a damping torque. Let's consider the problems arising at usage of permanent magnet and hysteresis rods for development of the attitude control system.

3.1. Mathematical Model

To analyse the motion of a satellite around its center of mass in order to check the correctness of ACS parameters choice and to generate these parameters the following equations are used

$$J\dot{\vec{\omega}} + \vec{\omega} \times J\vec{\omega} = \frac{3\mu_g}{r^3}\mathbf{E}_3 \times J\mathbf{E}_3 +$$

$$\mathbf{m}_s \times \mathbf{B} + \sum_{j=1}^{n} V_j W_j(\mathbf{H}\mathbf{e}_j, \dot{\mathbf{H}}\mathbf{e}_j)\mathbf{e}_j \times \mathbf{B}, (1)$$

$$\dot{\mathbf{E}}_j = -(\vec{\omega} - \dot{v}\mathbf{E}_2) \times \mathbf{E}_j, \quad (j = 1, 2).$$

Here J is a satellite's tensor of inertia, $\vec{\omega}$ is a vector of satellite's absolute angular velocity, $\mathbf{m}_s$ is a dipole moment of the permanent magnet, $\mathbf{e}_j$ is unit vector of j-th hysteresis rod, V_j is its volume, $W_j(\mathbf{H}\mathbf{e}_j, \dot{\mathbf{H}}\mathbf{e}_j)$ is a hysteresis function describing the relationship between rod's magnetization and external magnetic field applied, v is a true anomaly, n is an amount of rods, $\mathbf{E}_j$ is unit vector of the orbital reference system's j-th axis, $\mathbf{B} = \mu_0\mathbf{H}$ is a vector of the Earth's magnetic field induction. Upper dot ($\dot{}$) denotes the derivation with respect to a natural time t. In the circular orbit $\dot{v}$ is equal to a constant orbital angular velocity of satellite's center of mass ω_0. All vectors are determined by their projections on axes of body-connected reference system, whose axes are fixed in a satellite body. We have chosen axes coincided with satellite's principal central axes of inertia. Actually, we use three components $\omega_1, \omega_2, \omega_3$ of satellite's angular velocity vector $\vec{\omega}$ and six elements a_{11}, a_{12}, a_{13}, a_{21}, a_{22}, a_{23} of the directional cosines matrix as variables of task. Two indicated triplets of matrix elements are the components of unit vectors $\mathbf{E}_1$ and $\mathbf{E}_2$ respectively. Other three matrix's elements, which are the components of unit vector $\mathbf{E}_3$, are calculated by formula $\mathbf{E}_3 = \mathbf{E}_1 \times \mathbf{E}_2$.

Because of non-uniform rotation of a vector $\mathbf{H}$ in inertial space and varying its module during the satellite's centre of mass moving along the orbit it isn't possible to make *exact* orientation of satellite's longitudinal axis along this vector. Mathematically, it appeares because of the presence in right parts of equations discribing rotation of a satellite relative to the vector $\mathbf{H}$ the functions of a time due to non-inertiality of the reference system, which the satellite motion is considered in. It is possible only to be aimed to reduce amplitude of forced librations relative to the vector $\mathbf{H}$. The forced librations cause the possibilities of resonant relationship between natural frequencies of satellite and frequencies of forcing torque.

At manufacturing of the rods it is strictly necessary to maintain heating technological process. There are rather ruse precession motions of satellite, at which remagnetization of the rods happens along the particular loops of hysteresis. It results in slow reaching the steady-state motion by the satellite, that is, increasing the duration of transient motion. The possibility to reach such regime of motion fast depends on the ratio between moments inertia of satellite and initial conditions of its motion.

On the stage of engineering the magnetic attitude control system with hysteresis rods the following tasks are considered and solved:

- evaluating the frequencies of natural librations of satellite and measuring the vicinity of these frequences to the resonant zones, where the amplitude of librations can considerably be increased;
- the utmost significance of field intensity in satellite's body and in accordance with it to schedule the appropriate locations of magnet and rods installation were obtained;
- the required mass and size of the rods to manufacture them from available soft-magnetic materials were determined;
- the temperature at the places of the rod location was determined to compare it with Cureau temperature;
- the total magnetic moment of satellite in view of permanent magnet and magnetic elements of devices installed on the satellite was determined;
- the magnetic field intensity induced by instruments in location of hysteresis rods was estimated;
- the effect of daily rotation of the Earth on parameters of a steady-state motion was taken into consideration;
- discrepancy of axis of the permanent magnet magnetization and its geometrical axis of symmetry was evaluated.

3.2. Dipole Moment Determination

Let's temporarily ignore the effect of the hysteresis rods. The characteristic parameter, which determines the amplitude of forced librations and frequency of natural ones of the satellite relative to vector the $\mathbf{H}$ is dimensionless *magnetic parameter* η. It is defined as a ratio of characteristic value of a restoring magnetic torque $m_s B_0$ to the value of $I_y\omega_0^2$, conterminous by the form with characteristic value of a gravitational torque. Here m_s is a module of a dipole vector of the permanent magnet, B_0 is a module of the Earth's magnetic field induction vector over the equator, I_y is an equatorial moment of inertia of the satellite.

What does it mean the parameter η? At the satellite passing over the Earth's magnetic equator the value $\sqrt{\eta}/2\pi$ is close to angular frequency of the satellite's oriented axis libration relative to the vector **H**. Over the Poles the frequency is increased approximately in $\sqrt{2}$ times. Thus, as a dimensionless time the *latitude argument* u is chosen, that is, the period of satellite rotation around the Earth is equal to 2π.

The amplitude of satellite's forced librations relative to the vector **H** decreases in inverse proportion to the value of parameter η. In this case the steady-state motion of the satellite relative to the vector **H** could be obtained by a formal power series in η^{-1}. If the Earth's magnetic field is approximated by mathematical model in spherical functions power series with periodic in a time coefficients then the formal solution mentioned above has periodic in a time terms. Writing the liniarized equations of satellite motion in the vicinity of this formal solution it is possible to determine the approximate condition of untrivial, that is equalless to zero, solution existence

$$4\sin\left(\sqrt{\eta}a_s + \tfrac{1}{2}p\right)\sin\left(\sqrt{\eta}a_s - \tfrac{1}{2}p\right) - \frac{1}{2\sqrt{\eta}}q\sin\left(\sqrt{\eta}a_s\right) = O\left(\tfrac{1}{\eta}\right). \quad (2)$$

Here a_s, p, q are the coefficients depending on orbit inclination and axial velocity of satellite rotation. For simplicity the variant of axisymmetrical satellite is presented. The solution of equation (2) is

$$\eta = \frac{\pi^2k^2}{a_s^2} \pm \frac{\pi pk}{a_s^2} + \frac{p^2}{4a_s^2} + \frac{q}{4a_s} + O\left(\frac{1}{k}\right). \quad (3)$$

Here k is non-small integer value.

If we recall that the coefficients a_s, p, and q depend on the orbit inclination i then the curves in plane (η, i) show the place of areas in this plane lying in the vicinity ot these curves, where the amplitude of periodic motion of satellite increases. The terms kept in the linearized equations, which were

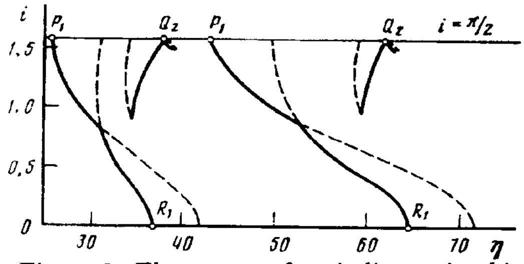

Figure 2: The curves of periodic motion bifurcation

mentioned above, don't allow to distinguish the curves, begining with the points of plane and spatial solutions bifurcation in the polar orbit. In Fig.2 the curves of bifurcation obtained by analysis of nonlinear equations of motion, where the effect of the hysteresis rods is ignored, are shown. Here points P_1 and Q_2 correspond to points of bifurcation of plane and spatial solutions in polar orbit respectively. Points R_1 correspond to bifurcation of motion in equatorial orbit. Under the approach used the bifurcation means that nontrivial solution of linearized equations in the vicinity of periodic motion with arbitrary amplitude exists. The number in subscript corresponds to periodic solutions of different symmetries [3]. Actually, these curves shows the parameter areas to be precluded during the satellite parameters choice.

The nominal motion was investigated under the periodic solution theory approach and a dipole moment of the permanent magnet was chosen under this approach. For obvious, the relationship between amplitude of forced periodic libration of axis of symmetry relative to the vector **H** and parameter η is shown in Fig.3. The magnitudes Am_α are obtained by formula $\mathrm{Am}_\alpha = \max_{0\le u\le\pi} |\alpha(u)|$, where $\alpha(u)$ is an angle between vector **H** and satellite's axis of symmetry in orbital plane. The discontinuities due to resonance are shown in this Figure near points marked by marker "×". It is seen that two periodic solutions appear near these point when magnetic parameter η increases. The abscissa of point marked by marker "×" is obtained from condition of the plane solution bifurcation. The abscissa of point marked by marker "Δ" is obtained from condition

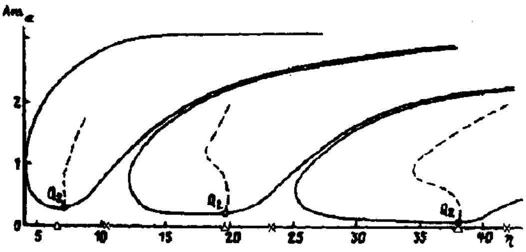

Figure 3: The amplitude curves of periodic motions of a satellite in orbital plane

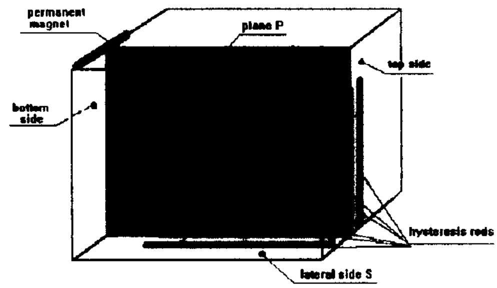

Figure 4: The scheme of hysteresis rods installation

of spatial solution bifurcation. These conditions are obtained for polar orbit. Under the "right dipole" model for approximation of the Earth's magnetic field, the rotaion of a satellite in polar orbital plane exists. The dash-lines mean the amplitude of spatial solutions, branching in resonance points Q_2. And, would seem, the increase of η promotes reduction of amplitude. However, the practice shows, that since the amplitude about $5-10°$ the main contribution to amplitude is caused by residual rotation around the axis of orientation and non-compensated residual magnetic moment of the hysteresis rods. The increase of η does not promote decreasing of these factors because the less amplitude of libration relative to the vector $\mathbf{H}$, the worse damping of speed of rotation around orientation axis and the stronger influence of the permanent magnet on hysteresis rods due to the small size of satellite.

After the preliminary study, the magnitude of the strong permanent magnet generated the restoring torque was chosen with a dipole moment of $0.3\,\mathrm{A}\cdot\mathrm{m}^2$.

3.2. Hysteresis Rod Parameters Deternination

The damping torque is generated by two identical groups of hystersis rods fabricated from soft-magnetic material and mounted on the mutual perpendicular lateral side S and the topside of the satellite in the planes, which are parallel and placed in the vicinity of the plane P crossing the middle of permanent magnet rod (Fig.4). The main requirements for mutial effect of rods and rods – permanent magnet are hereby performed. Such scheme of rod installation allows to minimize the effects:

— of mutial rods demagnetization;
— of strong permanent stabilizing magnet and payload instrument magnets onto the hysteresis rods;
— of rods onto steady-state motion due to their residual magnetization.

The equations describing the satellite motion around its center of mass were investigated by the *average method* under a small deviation of oriented axis of satellite from the Earth's magnetic field intensity vector $\mathbf{H}$ using different mathematical models of hysteresis. Due to the *Releigh model* of hysteresis, the hysteresis function W is

$$W(\dot{H}_\tau, H_\tau) = (\mu_{in} + \alpha_R H_{\tau m})H_\tau - \frac{\alpha_R}{2}(H_{\tau m}^2 - H_\tau^2)\,\mathrm{sign}\,\dot{H}_\tau, \qquad (4)$$

where μ_{in} is initial magnetic permeability of rod, α_R is a *Releigh's constant*, $H_\tau = \mathbf{He}$ is a projection of vector $\mathbf{H}$ onto a longitudinal axis of rod; we suppose that all rods are identical to each other; $H_{\tau m}$ is an amplitude of the remagnitizing magnetic field, that is, $H_{\tau m} = \max_{hysteresis\ loop} |H_\tau|$. Actually $\mu_{in} + \alpha_R H_\tau$ is a dependence of the magnetic permeability of rod on the current intensity of magnetic field H_τ under the initial magnetic permeability μ_{in} of rod. This model is correct for symmetrical relative to origin $H_\tau = \dot{H}_\tau = 0$ remagnetization process by as a shape, as a square of loop for small deviation of satellite with respect to the vector $\mathbf{H}$. By the Releigh model the square S_h of the hysteresis loop is expressed in parameters of model as

$$S_h = \frac{16}{3}\alpha_R H_{\tau m}^3. \qquad (5)$$

Introduce a "fast" time τ for parameter $\sqrt{\eta} \gg 1$ by a small parameter $\delta = 1/\sqrt{\eta} \ll 1$

via formula $\tau = (u - u_0)/\delta$ and consider axisymmetric satellite. In asymptotical sence the natural frequences of the satellite's axis of symmetry librations in orbital plane and in perpendicular plane are equal to each other. The small parameter δ allows to apply the averege methos to obtain the equations for evolution of slow variables including amplitudes of small librations of the axis of symmetry. The avereging over fast librations of the axis of symmetry produces equations that after coming back to independed variable u admits of the first integrals under absence of hysteresis rods. We show the most obvious one of them

$$(1 + 3\sin^2 i \sin^2 u)^{1/4}\,\mathrm{Am}_\theta^2(u) = c_1,$$

where i is an orbit inclination, c_1 is a constant of integration, Am_θ is an amplitude of deviation of the satellite's oriented axis with respect to the vector bf H.

Installation of two identical rods perpendicular to each other leads to cutting the terms in equations, which are proportional to the linear-depending on the intensity of the external magnetic field applied to the rods. The terms respecting with the nonlinear magnetization and hysteresis effects are left in the equations. The presence of terms proportional to a damping parameter $\varepsilon = \alpha_R V_b H_0^2/m$, V_b is a total volume of one of two groups of rods (or one rod), which are parallel to each other, allows to consider the constants of integration contained in the first integrals as new varables. So, the equation for the most intersting new variable c_1 takes the form

$$\dot{c}_1 = -\varepsilon\frac{4}{3\pi}(1 + 3\sin^2 i \sin^2 u)^{5/4} c_1.$$

It is easy to obtain its solution via quadrature

$$\mathrm{Am}_\theta(u) = \frac{\mathrm{Am}_\theta(u_0)}{(1 + 3\sin^2 i \sin^2 u)^{1/8}} \times$$
$$\exp\left(-\frac{2\varepsilon}{3\pi}\int_{u_0}^{u}(1 + 3\sin^2 i \sin^2 u)^{5/4} du\right) \quad (6)$$

It allows to estimate the main parameters of hystersis rods from the time-response point of view. Using the experimental estimated square S_h (see formula (5) for S_h above),

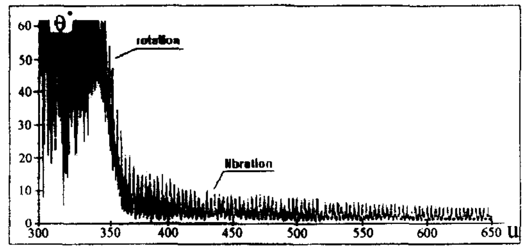

Figure 5: The angle θ of deviation of orientation axis of a satellite from vector **H**

it is possible to calculate α_R and determine the damping parameter. Of course such approach for the main parameters of attitude control system (the dipole moment of the permanent magnet and hysteresis rods) determination may be considered as a preliminary one only. Nevertheless, it couldn't be ignored owing its versality.

Unfortunately, finite-type-formula models do not describe properly the satellite motion in arbitrary mode. The numerically realised model that is based on the magnet-mechanical analogy [4] was justified and used to analyse the satellite dynamics and complete the hystersis rod parameter choice.

3.3. Numerical Investigation of Dynamics

The final calculations were executed under the following satellite's tensor of inertia

$$\begin{pmatrix} 0.0528 & -0.000068 & -0.000023 \\ -0.000068 & 0.0505 & -0.000046 \\ -0.000023 & -0.000046 & 0.0528, \end{pmatrix}$$

measured in kg $\cdot$ m^2, permanent magnet dipole moment $m_s = 0.3\mathrm{A}\cdot\mathrm{m}^2$, two triplets of rods $15.5\,cm$ length and $0.93\,cm^3$ total volume made from 79%Ni, 4%Mo, 17%Fe Permalloy (79NM), whose parameters are determined by Certificate, initial velocity of rotation $10°$/s or $175\omega_0$ in projections on each principal axes of inertia of satellite, orbit 705 km hight and inclination 98° given in [5]. The input of a weak eccentricity was considered too. The sample of transient motion is shown in Fig.5 with graph of angle θ of deviation of orientation axis of a satellite from vector **H** and in Fig.6 with components of angular motion $\omega_1, \omega_2, \omega_3$. The

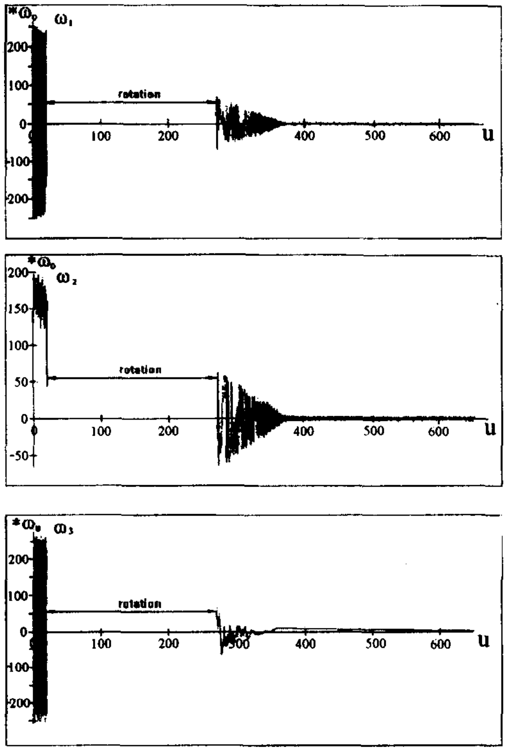

Figure 6: Components ω_1, ω_2, ω_3 of absolute angular velocity vector

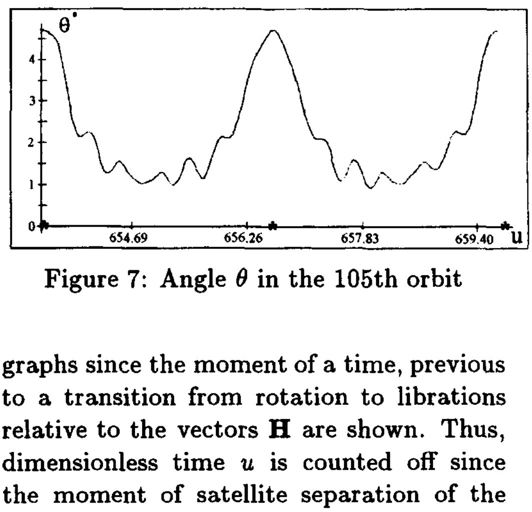

Figure 7: Angle θ in the 105th orbit

graphs since the moment of a time, previous to a transition from rotation to librations relative to the vectors **H** are shown. Thus, dimensionless time u is counted off since the moment of satellite separation of the launcher. The graph of almost steady-state angle θ in 105th orbit in integrated scale is presented in Fig.7. The marker "$\star$" on the abscissa axis means the moment of satellite passing over the equator. Approximately, in 60 orbits (less than four days) satellite has stopped the rotation and reached the regime of librations relative to the vectors **H** with amplitude about 20°. Further reduction of this amplitude is stipulated by reduction of

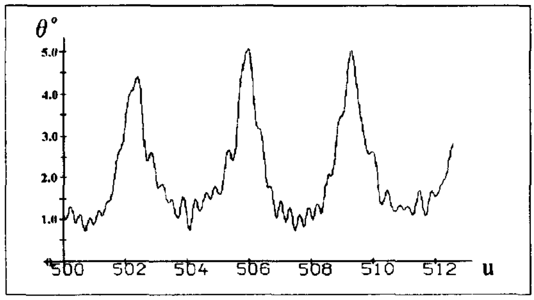

Figure 8: Angle θ near steady-state mode the under Gauss's model

axial speed of rotation. In 105th orbit the amplitude of librations has decreased to 4.7° at angular velocity of rotation about $3\omega_0$, which yet is decreasing. It is known [6], that the nature of motion of oriented axis is defined by relations between moments of inertia and defined by initial conditions of motion. For this reason the tensor of inertia was constructed to be closer to spherical one as possible.

These results of a steady-state motion modeling are obtained under the geomagnetic field dipole approximation. For comparability analysis of satellite dynamics was performed under standart Gauss's model of the Earth magnetic field IGRF-95. The graph of angle θ for almost steady-state motion obtained under the Gauss's model is shown in Fig.8.

The relationship between magnetized field along one of the rod and its magnetization normalized by suturated magnetization B_s, which is equal to 0.74 in the vicinity of steady-state mode of motion is shown in Fig.9. The "daughter" loops owing librations with frequence closed to natural one are evident in this graph. More details about MUNIN's ACS development process are presented in [7].

4. ATTITUDE DETERMINATION PROBLEM

The measurement data will be transmitted on ground each orbit owing the high latitude of Kirune (68° N, 20° E), where the mission control station is located. It is not necessary to know actual orientation of the

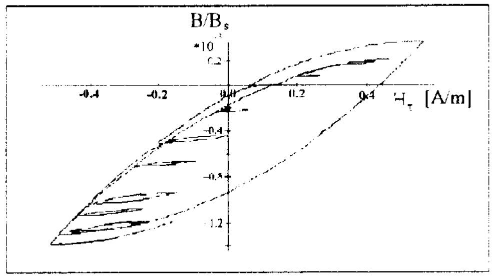

Figure 9: Relationship between magnetized field along one of the rod and its normalized magnetization

satellite MUNIN to control it but in order to interpret the measurement data of on-board instruments, the actual attitude motion of the MUNIN satellite should be determined. The measurements of the six solar arrays current, which cover each side of satellite's body, the data of two single-axis on-board magnetometers, which measure two components of the magnetic field inside the satellite, including the vector **H** of geomagnetic field, and pictures of the Earth's limb and stars by CCD-camera may be used. The data will be processed by on-ground station under the local and statistical mathematical methods taking into account the dynamical model of satellite and information about satellite's center of mass motion. The hard effect of the stabilizing permanent magnet and the magnets of instruments on magnetometers and effect of the Earth's albedo with rough measurement data of solar panel current as a sun-sensor compel to use the pictures of CCD-camera as more reliable information. Actually, there is no special sensors intended for attitude detrmination. The magnetometers available require careful calibration and accurate mathematical modeling of the magnetic field inside satellite's body, especially, the field generated by hysteresis rods. The algorithms for attitude determination are under development now.

5. CONCLUSION

The presented results of the passive magnetic attitude control system development may be applied for the development any passive ACS contained soft magnetic materials. This approach allows to develop inexpensive ACS, which may be used for non-complex microsatellites.

6. AKNOWLEGMENTS

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