ATTITUDE DETERMINATION AND CONTROL OF THE MIR ORBITAL STATION DURING SCIENTIFIC EXPERIMENTS

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ABSTRACT. Scientific experiments onboard the MIR space station require either fixed attitude in the orbital or inertial frames during experiment or its precise determination [1]. In this paper we consider the problems arising when planning the experiments and determining the station's attitude from onboard sensors measurement data [2].

1. THE ATTITUDE CONTROL SYSTEM OF THE MIR STATION

The MIR station is oriented in a special way in orbital or inertial equatorial (I) frames of reference most of time. Let us consider briefly the principles the MIR station Dynamic Control System (DCS) is based on [1]. DCS consists of two main units: Attitude Kinematic Unit (AKU) and Dynamic Stabilizing unit (DSU). AKU is designed for calculation of kinematic parameters (quaternions) determining the station's attitude in some basic frame of reference. DSU is designed for carrying the station into a certain attitude position given with respect to the basic frame of reference by quaternion R. For that purpose the gyro system and thrusters are used.

Basic frame of reference (inertial or orbital) is simulated by onboard computer. At first, an integral coordinate base I_M is calculated from the measurements of the station's absolute angular velocity $\overline{\ }$. Simulation of the base I_M is carried out by integration of kinematic equations in quaternions form: $2\dot{B} = B \circ \overline{\ }$, where B is quaternion determining station body frame attitude with respect to the base I_M . The attitude position of the inertial base I relative to the base I_M given by quaternion M is set a priory and corrected periodically with the help of special star trackers or sun and magnetic sensors. Therefore, the current quaternion A determining station body frame attitude with respect to the base I is calculated by formula: $A = \widetilde{M} \circ B$.

The orbital reference frame is calculated from a integration of the orbital motion equations by onboard computer.

2. MATHEMATICAL MODELS FOR THE MIR STATION CONTROL BY GYRO SYSTEM

The MIR station attitute control is based on gyro system which has its own kinetic moment $\overline{H}$ (t) depending on time. If $\overline{H}$ (t) achieves a tolerance limit, microthrusters provide instant unloadings of gyro system. To reduce fuel consumption slow unloadings with the help of gravitational torque are carried out. Great number of experiments, gyro unloadings and power supply from solar batteries problems require accurate mathematical modelling to optimize choice of the sequence of attitude modes. One of the stages of modelling is gyros kinetic moment accumulation forecast for different attitude modes. In our models we take into account gravitational and restoring aerodynamic torques acting on the station. Gravitational torque is described by usual analytic expressions. To calculate aerodynamic torque we approximate station's surface by a set of polyhedrons (Fig.1) [3]. We take into account that some planes, describing solar batteries can rotate about their longitudinal axes following the Sun. Besides, shading the parts of the station by another parts is considered.

Let us consider as an example the model of gyros kinetic moment accumulation during holding a certain attitude in the inertial frame of reference. The differential law for gyros own kinetic moment $\bar{H}$ is described by equation

$$\dot{\bar{H}} = \bar{M}_g + \bar{M}_a \qquad (1)$$

Here $\bar{M}_g$ and $\bar{M}_a$ are gravitational and aerodynamic torques. We assume here that all the external moments are got by gyros. For a given attitude this equation is solvable by quadrature and determine the gyros kinetic moment as a function of time. There are some restrictions to value of kinetic moment. When the solution of the equation (1) achieves the boundary of the available area, microthrusters unload gyros. Fig.2 illustrates gyro kinetic moment forecast in comparison with the measurement data obtained on June, 10, 1987 during observation of the source SN 1987 A. Station's attitude was fixed in inertial space. Here the markers depict measured component's of the Earth's magnetic field strength vector $\bar{H}$ in the station body system, and lines represent the graphs of that components, calculated with the help of the equation (1). The accuracy of the forecast of the moment of the next gyros unloading after known one is about 1 minute for intervals between two unloadings of about 1 hour.

Another problem is modelling the Euler turns of the station in the inertial frame. The model of the turn is based on simultaneous integration of equations for gyros kinetic moment and attitude differential equations. The simplest model uses the following differential equation for gyros kinetic moment

$$\dot{\bar{H}} = \frac{1}{\tau}\hat{J}(\bar{\omega} - w\bar{e}) - \bar{\omega} \times (\hat{J}\bar{\omega} + \bar{H}) \qquad (2)$$

Here τ is a positive constant, $\hat{J}$ is inertia tensor of the station, $\bar{\omega}$ is its absolute angular velocity, $\bar{e}$ is a unit vector of the axis of station's rotation in inertial space, w is a function of time.

If we substitute equations (2) into Euler dynamic equations for the station's attitude we receive the follows after simple transformations:

$$\dot{\bar{\omega}} + \bar{\omega} - w\bar{e} = \hat{J}^{-1}(\bar{M}_g + \bar{M}_a) \qquad (3)$$

Mathematical model of a turn is based on equations (2), (3) and kinematic equations for quaternion determining station body system attitude relative to inertial frame. A turn is controlled by choice of the function $w = w(t)$. For small values of τ station's angular velocity $\bar{\omega}$ is equal approximately $w\,\bar{e}$. The function $w(t)$ is determined by initial (before the turn) and resulting (after the turn) attitude quaternions and restrictions to $\bar{H}$ and $|\dot{\bar{\omega}}|$. Thrusters' runnings are not included into the model. The model allows to analyse whether thrusters' running occures or not during a turn and to predict the moment of the first one. The accuracy of the prediction is about several seconds. Fig.3 illustrates the example of turn modelling. Here the markers depict measured components of the vectors $\bar{H}$ and $\bar{\omega}$ in the station body system versus time, and lines represent graphs of that components calculated with the help of the model.

It is important to mention, that the station's inertia tensor can vary during the flight as a result of fuel consumption, cargo delivery, etc. So, it is necessary to adjust the inertia tensor to make models more accurate. Mathematical model for the gyro kinetic moment accumulation and measurements of the $\bar{H}$ vector allow to solve very interesting problem of estimation of the station's inertia tensor $\hat{J}$ in its body coordinate system [6,7]. The estimation is carried out by the least-squares method and uses solution of the equations (1) in its general explicit form

$$\overline{H} = \sum_{i=1}^{11} \overline{F}_i(t) \quad _i \tag{4}$$

Here $\overline{F}_i(t)$ depend definitely on station's orbital position and attitude, α_i (i = 1,...,11) are scalar parameters. The parameters for the leasts square method will be initial values of α_1, α_2 and α_3, which are the components of the $\overline{H}$ vector in the station body system, 3 non-diagonal components of inertia tensor $\hat{J}$ and two differences of its diagonal components (for example, $\alpha_4 = J_{yy} - J_{xx}$, $\alpha_5 = J_{zz}$, J_{xx}, $\alpha_6 = J_{xy}$, $\alpha_7 = J_{xz}$, $\alpha_8 = J_{yz}$,) and also aerodynamic parameters α_9, α_{10}, α_{11}. If we use formula (4) over a single interval of measurement data, we get a confluent case for the least-squares method. It is possible to avoid confluence in two ways: either to assume diagonality of the inertia tensor $\widehat{J}$ (i. e. $\alpha_6 = \alpha_7 = \alpha_8 = 0$) or to process measurement data over some intervals with different orientations simultaneously. In the latter case we assume, that parameters α_4, ..., α_8 are constant for all of the intervals, and another parameters may be different. The accuracy of estimation for α_4 and α_5 is several per cent and it is worse for α_6, α_7, α_8 estimation. In all the ways the following expressions are valid: $|\alpha_{6,7,8}| << \alpha_{4,5}$.

These models are the most important part of software for planning space experiments and operations. The other part is software for solving the inverse problem - attitude restitution from the measurement data.

3. ATTITUDE DETERMINATION OF MIR STATION

Most of scientific experiments onboard the MIR station require knowledge of the actual direction of a scientific device's axis of sight. The choice of a technique for solving this problem depends on required accuracy of attitude determination and station's dynamic mode.

If the required accuracy is not better than 1°, we use information from onboard computer in case of controlled motion or measurement data from onboard magnetometers in case of free drift.

In the former case we obtain components of the quaternion A which determine the body frame attitude with respect to the inertial equatorial coordinate system of epoch J1985.0. Deviations of the inertial base I does not exceed 1.5° per day. The position of the base I relative to the base I_M is corrected periodically using measurement data from star trackers and sun sensors.

In the latter case we use the statistical integral technique for station's free drift attitude determination by the measurements of the Earth's magnetic field strength vector $\overline{h}$. The station is assumed to move along a Keplerian orbit, free-stream density is calculated according to the dynamic model of atmosphere. The station's attitude motion is described by Euler dynamic and Puisson kinematical equations. Attitude determination technique is based on the least-squared method. The function characterizing mismatches between actual and predicted values of the vector $\overline{h}$ is minimized usually on a set of aerodynamic parameters and initial conditions of the station's attitude motion. It is possible to increase the number of adjusted parameters by the parameters describing station's own magnetic field, inertia tensor and calibration angles. The accuracy of the technique is about 1.5° - 2°.

If the required accuracy is better than 1°, it is necessary to involve into consideration measurement data from more accurate sensors, such as optical star camera "Astro-1". For the poiting phase in the inertial frame accuracy of attitude determination by the star camera measurements is better then 1 arcminute. With the help of "Astro-1" camera the estimation of accuracy of holding station's attitude by different means was carried out. In case of using gyro system the accuracy is about 3 arcminutes and in case of using thrusters it is about 1°.

In case of free drift we use an integral technique, as well as the local one to process the "Astro-1" data. Integral technique allows to process simultaneously the measurements corresponding to different moments. The technique is also based on the least-squares method and integration of the attitude equations. The accuracy of attitude determination by the "Astro-1" data for free drifts with low angular velocities (not exeeding the orbital angular velocity) is about 10 arcminutes. The example of attitude determination by star camera's data is represented in Fig.4. [10]. The curves represent the graths of the angles, describing station body system attitude position with respect to orbital frame, calculated according to the integral technique: β is the angle between station's longitudinal axis and orbital plane, δ is the angle between station radius-vector and projection of the longitudinal axis to the orbital plane and γ is the angle of rotation about longitudinal axis. Markers depict the values of those angles calculated by local technique.

For high-precise attitude determination it is necessary also to determine actual misalignment between axes of a scientific device and an attitude sensor. The technique of alignment calibration is the following. We construct the function of mismatches between measurements of scientific device and their predicted values, calculated for the nominal values of device's attitude position angles. The solution is found by minimization of the function on the set of attitude angles, describing relative attitude of the devices (for example, Krylov angles). Specific features of calibration procedure depend on a scientific device. For example, for the spectrometer MCS-2M calibration it was necessary to make several scanning of the Moon. For X-ray devices it is necessary to observe the celestial area with at least two bright X-ray sources. As an experience shows, the mismatches between nominal and actual angular positions of scientific and attitude devices may be up to some tens of arcminutes. It is necessary to mention, that the most of scientific equipment requiring high-precise attitude determination is mounted on the PRIRODA module, while the high-precise attitude sensors are installed onboard the another modules. Therefore, the next actual problem is to estimate the influence of flexibility of the MIR station to the results of alignment calibration.

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