Significance estimation of the rejected part of the signal spectrum from the magnetometer sensors of the prototype of the AIST small spacecraft

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Abstract. The paper presents the results of the investigation of the significance of the rejected part of the signal spectrum obtained from the magnetometer sensors. Sensors were installed in the prototype of the AIST small spacecraft. The measurement interval of the sensors significantly limited the spectral range of the measured signal from 0 to $\pi/6$ rad/s. The problem of significance of the signal spectrum rejected part was solved by restoring an analog signal from its discrete readings using the Kotelnikov series. Then the spectrum of the restored signal was constructed. In addition, the interval of simulated measurements was significantly reduced. Significance estimation of the rejected part of the signal spectrum allows us to make a conclusion about the accuracy of the signal restoration from the raw data. The results of our work can be used in estimating various characteristics in cases of abnormal operation of measuring devices or spacecraft's degraded performance.

1. Introduction

On December 28, 2013, the AIST small spacecraft prototype (Figure 1) was placed into the near-circular orbit with an altitude of 625 km and an inclination of 82.40° [1]. The mass of the AIST small spacecraft was 39 kg and the mass of scientific hardware was 11 kg.

Figure 1. General view of the AIST small spacecraft prototype.
Two three-component magnetometer sensors were used as the main measuring devices for estimating the parameters of the rotational motion of the AIST small spacecraft. The angular velocity sensors are inferior in mass to the magnetometer sensors and can show false measurements of angular velocity, for example, when the large elastic elements of the spacecraft are vibrating [2].

The angular velocity of AIST small spacecraft rotation was estimated by the following recurrence formula [3]:

\[
\omega_{i+1} = \arccos \left( \frac{B_{x_i} B_{x_{i+1}} + B_{y_i} B_{y_{i+1}} + B_{z_i} B_{z_{i+1}}}{|\vec{B}_i| |\vec{B}_{i+1}|} \right),
\]

where \(\vec{B}(B_x, B_y, B_z)\) are components of the induction vector of Earth's magnetic field, measured by magnetometer sensors at time points \(t_i\) and \(t_{i+1}\).

The problems of estimating the small spacecraft angular velocity by measurements of the components of the induction vector of the Earth’s magnetic field are well-studied and widely presented in papers of various authors, for example [4-7]. The unique feature of AIST small spacecraft was an algorithm for the measurement data generation. To increase the data accuracy, the moving-average method was used [8,9]. Thus, measurements of the components of the induction vector of the Earth’s magnetic field were recorded in telemetry data with the 6-second interval. It significantly limits the frequency domain of the measured signal. In fact, measuring a signal with 6 second interval means that its spectrum should not contain significant harmonics with a frequency higher than \(\pi/6\) rad/s [10]. Such assertion requires separate verification. The paper is devoted to this verification.

2. Materials and methods

The session on September 2, 2014 was selected as the measurement data. A sample of 64 measurements was taken from this session. It corresponds to a time interval of 384 seconds. The measurements were chosen so that the telemetry data on this part did not contain incorrect data. The discrete Fourier transformation was used as a signal processing method [10]. Restoration of the signal was carried out by Kotelnikov series [11].

3. Results and discussion

The raw signal is shown in Figure 2. The raw signal was measured by the X channel of the first sensor of the magnetometer of the AIST small spacecraft with the 6-second discretization interval.

Figure 2. Results of the measurements of the Bx1 component of the Earth's magnetic field induction vector's by the first sensor of the magnetometer of the AIST small spacecraft.

The signal spectrum was obtained using the discrete Fourier transformation [11]:
\[ X_k(e^{i\omega}) = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi in}{N}}, \quad k = 0, \ldots, N - 1 \]  

where \( X_k \) is the k-th spectral characteristic; \( x_n \) is the n-th dimension; \( N \) is the number of measurements.

Figure 3 shows the discrete gain frequency characteristics of the signals from Figure 2 and from the related channel Y of the second sensor of the magnetometer of the AIST small spacecraft. As the raw data for the discrete Fourier transformation 64 measurements were selected from the channel X of the first sensor and from the channel Y of the second sensor.

As can be seen from Figure 3, the signals have the similar spectral characteristics, however, as the author of [1] notes, there is a significant shift in the average values of these signals. The authors of [3] propose to use only the data from the second sensor of the magnetometer in the reconstruction of the rotational motion of the AIST small spacecraft. The data from the second sensor of the magnetometer is closer to the estimates of the components of the induction vector of the Earth’s magnetic field, which were carried out by the standard model of the Earth’s magnetic field. In [1], a statistical test was carried out for the anomalous measurements of the first sensor of the channel X. Prerequisites for such a test were two features.

1) The average value of the measurement data for the channel X of the first sensor turned out to be less in all measurement sessions than for the other five channels of the first and second sensors. At the same time for the related measurement channel Y of the second sensor such a situation was not observed.

2) The measurements dispersion for the channel X of the first sensor also turned out to be minimal among all six measurement channels in all measurement sessions.

However, the test results were negative. Three different statistical criteria used in [1] rejected the hypothesis about the anomalous measurements of the channel X of the first sensor. Therefore, in [1], it was assumed that the scientific and supporting equipment of the AIST small spacecraft at its operation most influenced on this measurement channel. The reason for such a selective influence on the onboard measuring devices could be a feature of the layout of the equipment and sensors of the measuring devices in the AIST small spacecraft. However, such investigations have not been fully carried out.

Is it possible to level the potential influence of the scientific and supporting equipment and to increase the measurement accuracy for the channel X of the first sensor? Or the only way to correctly reconstruct the movement is to ignore the measurement data of the first sensor, as proposed in [3]. Such a question may be relevant not only with the equipment’s influence on the onboard measuring devices, but also with their degraded performance. We will restore the analog signals corresponding to the gain frequency
characteristics on Figure 3, using the Kotelnikov series according to their discrete readings [11]:

\[
x(t) = \sum_{n=0}^{\infty} x(nT) \frac{\sin \left( \frac{\pi}{T} (t - nT) \right)}{\frac{\pi}{T} (t - nT)},
\]

(3)

where \( x(t) \) is a continuous function, with the exception of the points of the raw measurements at \( t = nT \); \( T = 6 \) s is the measurement interval.

**Figure 4.** Comparison of the analog signals of the components of the induction vector of the Earth’s magnetic field restored by the Kotelnikov series: 1 is \( B_x \) (the channel X) of the first sensor; 2 is \( B_y \) (the channel Y) of the second sensor.

To estimate the significance of the rejected part of the spectrum and to level the possible influence of the scientific and supporting equipment on the measuring devices, we simulate the measurements with \( T = 3 \) s interval, i.e. twice as much as the real measurements. We will add the missing measurements from the recovered signal (Figure 4). We construct the gain frequency characteristics of the raw \( (T = 6 \) s \) and simulated \( (T = 3 \) s \) signals in the frequency domain from 0 to \( \pi/6 \) rad/s (Figure 5), as well as the simulated signal in the frequency domain from 0 to \( \pi/3 \) rad/s (Figure 6). Their comparison shows that the average value of the simulated signal is higher than the average value of the raw signal. The spectrum part of the simulated signal in the frequency domain from \( \pi/6 \) to \( \pi/3 \) rad/s is less significant than in the frequency domain from 0 to \( \pi/6 \) rad/s. It allows us to try to improve the quality of the raw data. In theory the majority control method is known for the quality of the raw data obtained from the measuring devices. This method is described and applied, for example, in [12]. We use the simulated measurements as an additional measurements channel. Denoting the weighting coefficients to the real and simulated measurements, we get the corrected signal. The gain frequency characteristics are shown in Figure 7 for the corrected signal and the raw signal of the second sensor in the frequency domain from 0 to \( \pi/6 \) rad/s. As can be seen in Figure 7, the difference between the signals has become significantly smaller.
4. Conclusion
Thus, it is found that:

- the spectrum part in the frequency domain from 0 to $\pi / 6$ rad/s is the most significant according to the simulated measurements made by the raw data and the analog signal restored by the Kotelnikov series;

Figure 5. Comparison of the gain frequency characteristics of the measurements in the frequency domain from 0 to $\pi / 6$ rad/s: 1 is the real measurements ($T = 6 \text{ s}$); 2 is the simulated measurements ($T = 3 \text{ s}$).

Figure 6. The gain frequency characteristics of the simulated measurements.

Figure 7. Comparison of the gain frequency characteristics: 1 is the corrected measurements from the channel X of the first sensor; 2 is the measurements from the channel Y of the second sensor.
the application of the majority control method with using the simulated measurements as an additional measurement channel made it possible to significantly approximate the measurements of the first sensor to the measurements of the second sensor that were considered suspicious to an anomaly [1] and rejected during the reconstruction of the rotational motion of the AIST small spacecraft.

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