A STRAPDOWN INERTIAL NAVIGATION SYSTEM FOR SPACE LAUNCH VEHICLES: INITIAL ALIGNMENT ACCURACY AND PERIODIC CALIBRATIONS*

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***Abstract*—Reaching initial alignment accuracy and implementation of periodic calibrations during the time of INS performance are problems to solve with the view to embedding Strapdown INS in control systems of space launch vehicles and spacecraft. Possible solutions to these problems are proposed. The efficiency of the proposed techniques is proved by the mathematical simulation and experimentally with the help of the inertial measurement unit IMU-501 developed and produced by Research and Production Company "Optolink" (Russia).**

Keywords—strapdown inertial navigation system, launch vehicle, angular rate sensor, initial alignment, calibration

I. INTRODUCTION

A common tendency of INS development, including space applications, is the gradual switch to Strapdown INS (SINS), which have essential advantages of some technological and operational characteristics in comparison with gimballed INS. Theoretical and experimental studies aimed at development and use of SINS in control systems of space launch vehicles (SLV) and spacecraft have been carried out at Academician Semikhatov Scientific and Production Association of Automatics (SPAA) since the 1970-s.

SPAA named after academician Nikolai Semikhatov, founded in 1952, is one of the leading Russian companies in development and production of control systems for ballistic rockets and space launch vehicles. The outstanding engineer and researcher Nikolai Semikhatov, whose 100th anniversary is celebrated in 2018, was General Designer of SPAA from 1952 to 1992. SPAA was the first company in the Soviet Union to embed digital computers (the 1960s), star trackers (the middle of the 1970s), and satellite navigation systems (the middle of the 1980s) in the control systems of ballistic rockets.

In 1993, SPAA began developing a control system for the medium-lift launch vehicle Soyuz-2, designed and produced at Space Rocket Centre "Progress" (Samara). Soyuz-2 was launched in 2004. After that, cooperation with the French National Centre for Space Studies and European Space Agency resulted in Souyz-2 modification intended for launches from the spaceport Kourou in French Guiana. Nowadays Soyuz-2 places satellites of Global Navigation Systems, satellites for Earth remote sensing and scientific researches, and spaceship Progress, carrying cargo to the International Space Station, in various orbits. Beginning from 2004, there have been 75 successful launches including 18 launches from French Guiana.

Inertial navigation accuracy for SLV Soyuz-2 is ensured by a gimballed INS with an Inertial Measurement Unit (IMU) developed and produced at Scientific and Production Association of Electromechanics (Miass, Russia). At the time when principal technical decisions concerning the control system of the SLV Soyuz-2 were being made, this gimballed IMU was better as a whole than Strapdown Inertial Measurement Units (SIMU) produced in Russia. The progress in development and production of precise inertial sensors for SINS in Russia serves as the basis for switching from traditional gimballed INS to SINS in control systems for prospective SLV.

At present, SPAA is developing high accuracy SINS for prospective space launch vehicles and spacecraft, which is a part of Federal Space Program for 2016-2025, and a SINS for reusable suborbital space complexes for space tourism according to the draft proposal of JSC Kosmokurs. Some problems of development of such SINS were considered in the papers presented by SPAA engineers and researchers at the previous St. Petersburg conferences. In this paper, some problems of prelaunch preparation are considered. One of them is assurance of initial alignment accuracy. The other one is implementation of SIMU periodic calibrations during its operation.

II. ASSURANCE OF INITIAL ALIGNMENT ACCURACY

Space launch vehicles, especially orbiting manned spacecraft, must meet rather high accuracy requirements of INS initial alignment. This results in high requirements of IMU accuracy parameters and their stability both from-run-to-run and in-run. For gimballed INS, required initial alignment accuracy is reached with the help of two-position gyrocompassing and, if necessary, prelaunch calibration. The initial alignment errors (3σ, σ is a standard deviation) of Soyuz-2 gimballed INS are about 6-7 arcsec in levelling and 1.7 arcmin in azimuth, which provides required accuracy in reaching a predetermined point of an orbit even in inertial mode.

The requirements for initial alignment accuracy of aided SINS for prospective space vehicles are (3σ) 15-30 arcsec in levelling and from 5 to 30 arcmin in azimuth determination. Levelling accuracy can be ensured by accelerometers with in-flight accuracy characteristics, which are $(3\text{-}10)\cdot10^{-4}$ m/s^2 in the bias error and 0.002-0.01% in the scale factor error. With state-of-the-art accelerometers, it is not a problem.

The requirements for angular rate sensor (ARS) bias, which is the main source of gyrocompassing error, may turn out to be more stringent for the initial alignment than for the flights. These errors are restricted by 0.015 arcsec (at the latitude 45°) to provide azimuth accuracy of about 5 arcmin whereas 0.05-0.1 arcsec/s are sufficient to provide in-flight accuracy. Various solutions of this problem (in particular, the use of high accuracy expensive ARS, which, in addition, may not meet the requirements of mass and volume or azimuth alignment with the help of optical measurements, which is an expensive solution as well) were analysed. The analysis has shown that the use of a simple rotary device, on which a SIMU is fixed, may be the most efficient solution. This approach is known to be used for gyro drift autocompensation in strapdown heading indication systems. With such a device, SINS azimuth alignment accuracy can be improved by means of two-position gyrocompassing in the same way as alignment accuracy of a gimballed INS. SIMU output data are processed in two positions spaced apart with respect to the vertical axis. After the rotation, the rotary device and SIMU are strictly fixed.

To implement two-position gyrocompassing, we should provide the optimal choice of the rotation angle. If the main source of azimuth estimation error is in-run instability of ARS biases (or of gyro platform drifts) and the rotation itself is implemented with sufficient precision, the rotation angle of 180° proves [1] to be optimal. Since errors of gimbal angular sensors are about a few arcsec, the rotation accuracy in gimballed IMU is sufficiently high, which is why two-position gyrocompassing is carried out in Souyz-2 with the rotation angle of 180°.

To eliminate rotation errors as a source of azimuth estimation error, a SIMU should be rotated about the vertical axis by 90°. Such a technique of azimuth alignment, based on two-position gyrocompassing with the help of relatively inaccurate rotation device, is proposed in paper [2]. It involves prelaunch calibration of the biases of all the ARS included in SIMU as well. The procedure of initial alignment and calibration involves coarse alignment and fine alignment with two iterations if necessary. The results of mathematical simulations have shown that, under sufficient in-run stability of SIMU accuracy parameters, azimuth alignment accuracy improves by an order and ARS biases errors decrease by a factor of 10-20. The requirements for misalignment angles between the rotation axis and the sensor axes and those for rotation angle errors are about 1-2°.

The technique was verified both with the help of mathematical simulation and experimentally with a real IMU-501 developed and produced by Research and Production Company “Optolink” (Russia). It includes three fiber-optic gyros (FOG) and three quartz pendulum accelerometers with orthogonal input axes. The IMU-501 test results obtained by means of SPAA test equipment not only validated but, for some parameters, proved to be even better than in the manufacturer specifications. In particular, from-run-to-run instability (3σ, 10 runs) was 0.06÷0.08 mg (as compared with 0.3 g in the manufacturer specifications) for accelerometer biases, 0.015÷0.02 arcsec/s (as compared with 0.09 arcsec/s in the manufacturer specifications) for FOG biases. A SIMU with such accuracy parameters allows for levelling with accuracy of about 13÷17 arcsec, for azimuth accuracy of about $(3.4\div10.3)\cdot(\cos\varphi)^{-1}$ arcmin (φ is a latitude of a launch spot), which is quite sufficient for some applications.

7 runs were carried out to estimate ARS biases with the help of the gyrocompassing technique. In each run, IMU-501 was put successively in 5 orientations rotated relative each other by 90°. After the second iteration, the maximum value of ARS bias error (3σ) was $2.6\cdot10^{-4}$ arcsec/s, which yields azimuth error of about $3.6\cdot(\cos\varphi)^{-1}$ arcsec. Thus, SINS azimuth alignment can provide the same accuracy as that of a gimballed INS, even taking into consideration other error sources (accelerometers errors, inaccuracy of a rotary device, wind oscillations during the prelaunch preparation).

If prelaunch lifting of a spacecraft from the horizontal position to the vertical one is carried out with a running navigation system, gyrocompassing accuracy can be improved due to a two-position scheme with rotation about the horizontal axis. In the first horizontal position, the vertical ARS is calibrated; after rotation to the vertical position, this ARS is oriented horizontally and is used to determine an azimuth angle. This technique can improve gyrocompassing accuracy by one to two orders as well, if an angle between the rotation axis and the East axis is more than 10° [3].

III. SIMU ACCURACY CHECKING AND CALIBRATION

It is necessary to check accuracy characteristics and regularly calibrate SINS during its operation. Calibration involves SIMU special orientations and rotations relative to the geographical frame, which is not a problem for a gimballed INS. Calibration of a gimballed INS is carried out on a vehicle without demounting either during prelaunch preparation on the launch complex or during regular checking on the technological complex where a launch vehicle is oriented horizontally.

Accuracy checking of an SIMU mounted on a vehicle can be implemented only indirectly by estimating magnitudes of measured vectors (the local gravity and the Earth angular rate) and an angle between them. SINS calibration either with the view to estimating error model parameters caused by aging or between-flights calibration for a reusable SINS can be carried out only if a SIMU, or a SINS in whole, can be demounted and then mounted again on a vehicle. Such a possibility is provided for prospective space launch vehicles and spacecraft. In particular, the specifications of the control system for reusable suborbital space complexes include maintainability and possibility to change failed components and units during the launch preparation.

It is known [4], [5] that bench calibration of SIMU basic accuracy parameters can be carried out with the help of a simple two- or three axes turning table with accuracy of about 1-2°. This table along with checking and testing hardware including technological interface for reading SIMU outputs, computer, and software for preprocessing and post processing is a part of hardware of a technological complex. In this way, SIMU calibration and maintenance are possible at a launch spot without sending it back to the factory. The results of calibration can be used for software compensation in the subsequent SINS operation.

The technique of bench calibration developed in SPAA does not need a precise rotation table allowing for calibration of all the SIMU basic errors including ARS scale factors and misalignments. The calibration procedure is subdivided into three stages based on physical interpretation: 1) calibration of scale factors, biases, and misalignments of accelerometers, 2) calibration of ARS biases, 3) calibration of ARS scale factors and misalignments.

The first and the second stages are implemented in a static mode using direct measurements of projections of the normal reaction of the local gravity and the Earth rate. After the known techniques of direct calibration, including scalar calibration [4], were analysed, a new method was developed. As well as scalar calibration, it does not require precise program angular orientations and has the same accuracy, but its algorithms are simpler. The program orientations with maximum observability of different groups of parameters are used, and corrections of determined parameters by physical “non-horizon” angles are taken into consideration. “Non-horizon” angles are estimated with the help of horizontal accelerometers. At the first stage, an SIMU is put in 9 program orientations and is fixed in each one for 5 minutes. At the second stage, there are 3 program orientations fixed for 10-15 minutes.

According to the analytical estimations, methodical errors of accelerometers calibration have the order of the product of a physical “non-horizon” angle and an accelerometer error and form 1-2% of estimated parameters. These errors can be reduced additionally by an order with the help of an iteration procedure. The results of estimation of from-run-to-run instability (7 runs) of IMU-501 accelerometer parameters are shown in Table 1. In the process of the second iteration, accelerometer errors were compensated for using the results of the first iteration so that the errors obtained in the second iteration characterise the errors of the first iteration. As it may be seen from Table I, the experimental estimates are close to the analytical ones. Thus, the main source of accelerometer calibration errors is in-run instability of estimated parameters.

TABLE I.

From-run-to-run instability (3σ) of IMU-501 accelerometer accuracy parameters					
Scale factors, %		***Biases, m/s2***		***Misalignments, arcsec***	
1st iteration	***2nd iteration***	***1st iteration***	***2nd iteration***	***1st iteration***	***2nd iteration***
$(5.0\div7.7)\cdot10^{-3}$	$(2.1\div6.1)\cdot10^{-5}$	$(5.5\div8.3)\cdot10^{-4}$	$(1.4\div6.7)\cdot10^{-5}$	$13.2\div14.0$	$0.3\div1.0$

At the second stage during which ARS biases are calibrated, the accelerometer errors are compensated for by the results obtained at the first stage. According to the analytical results, the ARS bias estimation error is a sum of two components. They are the product of a physical “non-horizon” angle about the East axis and an error of the equivalent North accelerometer and the product of a physical “non-horizon” angle about the North axis and an error of the equivalent East ARS. Since the accelerometers were calibrated at the first stage, the main error source is ARS bias error. The calibration error forms 1-2% of the estimated parameter as well. The analytical results are confirmed by the experimental estimates of from-run-to-run instability (7 runs) of IMU-501 ARS biases shown in Table II.

TABLE II.

From-run-to-run instability (3σ) of IMU-501 ARS biases, arcsec/s					
Axis X		*Axis Y*		*Axis Z*	
1st iteration	***2nd iteration***	***1st iteration***	***2nd iteration***	***1st iteration***	***2nd iteration***
$3.42\cdot10^{-2}$	$1.83\cdot10^{-4}$	$2.14\cdot10^{-2}$	$1.69\cdot10^{-4}$	$2.73\cdot10^{-2}$	$2.74\cdot10^{-4}$

At the third stage, the indirect calibration technique is used. The calibration procedure consists of a sequence of rotations, each separated by a pair of orientations at fixed positions. The technique is similar to the one widely used in the USA and Europe for calibration of aviation SINS in the field at remote facilities [5]. It allows for calibration of all the SINS accuracy parameters except for accelerometer scale factors and ARS biases. These parameters are calibrated at the first and the second staged and are compensated for at the third stage. The results of the indirect calibration of IMU-501 accelerometer biases and misalignments are close to those obtained by the direct calibration (Table I). The estimates of from-run-to-run instability of ARS scale factors and misalignments obtained by the indirect calibration technique are presented in Table III.

TABLE III.

From-run-to-run instability (3σ) of IMU-501 ARS accuracy parameters			
Scale factors, %		***Misalignments, arcsec***	
1st iteration	***2nd iteration***	***1st iteration***	***2nd iteration***
$(0.6\div1.6)\cdot10^{-2}$	$(0.15\div1.25)\cdot10^{-3}$	$(0.6\div1.6)\cdot10^{-2}$	$(0.15\div1.25)\cdot10^{-3}$

IV. CONCLUSION

The results of the theoretical and experimental studies carried out in SPAA have shown that specified accuracy of initial alignment and periodic calibrations of SINS for space launch vehicles and spacecraft can be reached with the help of relatively simple and reasonably priced equipment.

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