Characteristics of the Satellite System for Landing the Aircraft on a Mobile Platform when Stabilizing the Glide Path Using Microelectromechanical Sensors

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***Abstract* — The article investigates the accuracy characteristics of determining the aircraft location using mathematical modeling of errors of inertial microelectromechanical sensors for a GNSS landing system on a mobile platform in pitching conditions.**

Keywords* — *aircraft landing, global navigation satellite system, relative navigation, microelectromechanical sensors

I. INTRODUCTION

The strategy for the development of the Russian aviation industry until 2035 [1, 2] provides for the creation of unmanned aerial systems for communication, monitoring and cargo transportation.

An urgent task for both manned and unmanned aerial vehicles (AV) is ensuring safe landing, the success of which is due to, among other things, the radio equipment of airfields. Instrument landing systems of the ILS type, radar systems of the RSP type (radar landing system) are currently installed at large civil aviation airfields; landing systems of the PRMG type (landing beacon group) are installed at state airfields; landing systems such as PRLK (landing radar system) and MLS (microwave landing system) are installed on large aircraft carriers of the Russian Navy [3, 4, 5].

Currently, the main line in the development of landing systems is using the solutions based on GNSS with functional additions (GBAS/LCCS, SBAS) [3]. The widespread introduction of such systems is facilitated by the high accuracy of determining the navigation parameters of the AV, low requirements for weather conditions during operation, the global coverage area, as well as the relatively low cost of on-board and ground equipment. To improve the accuracy, continuity and integrity of the information of the GNSS landing system (GLS), small-sized strapdown inertial navigation systems (SINS) based on sensors built using microelectromechanical systems (MEMS) technology are being actively introduced as part of the equipment.

The tasks of landing aircraft on stationary landing pads, platforms and airfields using GNSS, GBAS/LCCS, SBAS have now been studied in sufficient detail and are being widely implemented in civil aviation [3]. The use of small-sized SINS made on MEMS sensors in on-board equipment is also widely discussed and has many implementations. At the same time, the problem of landing on a mobile landing platform in pitching conditions using relative navigation according to GNSS data has not been sufficiently studied to date.

The aim of the work is to estimate the errors in determining the aircraft location due to errors in the stabilization of the synthetic glide path in the GLS when modeling the random drift of the zero value of the MEMS sensors and various locations of the GNSS antenna and the calculated landing point (CLP) to determine the possibility of automatic landing of the AV on a mobile platform in pitching conditions.

II. ACCURACY OF THE GNSS NAVIGATION SOLUTION IN RELATIVE MODE

To determine the necessary accuracy of stabilization of the landing point (that is, the point of intersection of the glide path with the plane of the landing pad) when using a synthetic glide path in the GLS with a relative mode of determining the range and lateral deviations of the aircraft from the glide path, it is necessary to set the maximum permissible errors in determining the coordinates of the landing point (LP) location. On a stationary basis, these errors are associated only with errors in the navigation solution of the GNSS receiver.

On a mobile base, the GNSS antenna and the landing point are always separated by some distance from each other both in the horizontal plane and in height. The GNSS antenna is installed as high as possible to avoid shading the celestial hemisphere over the antenna structures of the platform itself. When the platform is tilted, these distances become the shoulder of the mutual displacement of the landing point and the phase center of the GNSS antenna

(PCA) in the coordinates of the local horizon. To measure the angles of inclination, it is advisable to use inertial sensors of the MEMS type.

Considering the fact that the total measurement error of the unmanned AV location in the GLS must meet, at least, the requirements for category III [3], which are no more than 6 m in horizontal coordinates, and in vertical coordinates – no more than 2 m with a probability of 0.95, and taking into account that the measurement errors in the relative GNSS mode are 0.2 m in horizontal coordinates and 0.5 m in height with a probability of 0.95 [6], it can be argued that the additional error introduced into the determination of the location of the AV due to errors of inertial sensors affecting the accuracy of stabilization glide paths should not exceed 5.9 m in horizontal coordinates and 1.9 m in height with a probability of 0.95.

III. THE IMPACT OF PITCHING ON LOCATION ERRORS

To estimate the limit values of deviations, consider pitching as a combination of linear and angular oscillations. Linear oscillations can occur both in the vertical plane and in the horizontal, while the center of gravity of the platform with all the equipment on it is shifted. Such offsets are easy to register using a GNSS receiver with a single antenna. The accuracy of determining these offsets depends entirely on the accuracy of the navigation solution of the GNSS receiver. The second type of oscillation is angular. Angular oscillations of the platform, in general, also occur around all three orthogonal axes: roll, trim, yaw. The roll and trim cause a deviation of the vertical axis. We will consider the process of pitching, the amplitude of the roll and trim angles at which do not exceed 15˚ and 5˚, respectively. Pitching with a roll of up to 15˚ usually does not cause a shift in the center of gravity [7], which ensures the linearity of the description of the acting forces and the uniformity of the pitching process. The angular oscillations of the platform around the vertical axis have an insignificant amplitude and a sufficiently long period, which makes it almost impossible to adequately measure these oscillations without the use of navigation-class accuracy sensors, to which MEMS-type sensors do not belong. If the heading direction of the platform is maintained constant, then the displacements of the PCA relative to the LP of the platform will be caused by the swing of the platform only at the angles of the roll and trim. Expressions for converting offsets from the associated coordinate system (ACS) to the local level frame (LLF) have the form [8]:

$$\begin{bmatrix} \Delta_X \\ \Delta_Y \\ \Delta_Z \end{bmatrix} = \begin{bmatrix} C_p & S_p S_r & S_p C_r \\ 0 & C_r & -S_r \\ -S_p & C_p S_r & C_p C_r \end{bmatrix} \cdot \begin{bmatrix} \Delta_r \\ \Delta_p \\ \Delta_y \end{bmatrix}, \tag{1}$$

where Δ_X, Δ_Y, Δ_Z – displacement vector components in LLF, Δ_r, Δ_p, Δ_y – displacement vector components in ACS, S_r and C_r – sine and cosine of the roll angle, S_p and C_p – sine and cosine of trim angle.

Thus, when forming a synthetic glide path, the PCA displacement relative to the LP in the LLF becomes an additional error in determining the coordinates of the aircraft in the relative navigation mode. These linear displacements are functions of the roll and trim angles.

In pitching conditions with low dynamics of changes in roll and trim angles, angles can be measured using an inclinometer built on a triad of micromechanical accelerometers, since tangential and centripetal accelerations are insignificant. For conditions with high dynamics of angular motions during pitching, the use of angular velocity sensors is required in order to account for non-gravitational accelerations, which significantly complicates processing algorithms. Expressions are used to determine the roll and trim angles:

$$roll = \arctan\left(\frac{a_p}{a_y}\right); pitch = \arctan\left(\frac{-a_r}{\sqrt{a_p^2 + a_y^2}}\right), \tag{2}$$

where a_r, a_p, a_y - components of the projection of the specific force vector on the ACS axis, *roll* – true bank angle, *pitch* – true trim angle.

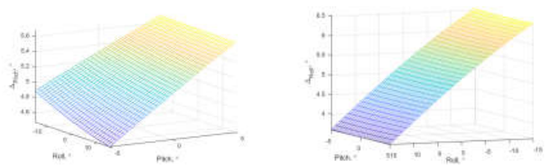
Consider the errors of MEMS accelerometers. All assemblies of inertial sensors must undergo a calibration procedure to calculate temperature displacements, zero readings, scale factor in the measurement range, as well as angles of non-orthogonality. During calibration, it is impossible to eliminate measurement errors that are caused by random drift of the zero value both from run to run (repeatability) and within each run (instability). The zero drift from run to run for MEMS-type sensors, as a rule, exceeds twice or more the magnitude of the instability of the zero value according to Allan variations in run [9, 10] and varies from 0.1 mg to 100 mg for modern MEMS sensors.

To estimate the error of the platform angles of inclination, we use expressions (2), presenting the parameters included in them as a true value and a random error:

$$\begin{aligned} roll' &= \arctan\left(\frac{a_p + a_\Delta}{a_y + a_\Delta}\right); \\ pitch' &= \arctan\left(\frac{-(a_r + a_\Delta)}{\sqrt{(a_p + a_\Delta)^2 + (a_y + a_\Delta)^2}}\right), \end{aligned} \tag{3}$$

where a_Δ – random zero shift of acceleration sensors, *roll'* – measured roll angle, *pitch'* – measured trim angle.

The error in determining the angles of roll and trim during pitching within the specified limits of the change in the angles of inclination of the platform is determined by the modulus of the angle difference obtained in accordance with expressions (2) and (3). The results of calculating these errors are shown in Fig. 1.



a) b)

Fig. 1. Angle error distributions with a random zero offset of the acceleration sensors by 10 mg. a) Trim angle error. b) Roll angle error.

Consider three ranges of zero shift repeatability of acceleration sensors: 0.001 g, 0.01 g, 0.1 g. When calculating, we use the maximum values of deviations in the angles of roll and trim for each range of zero shift repeatability.

The values of the root-mean-square error (RMS) of location determination depending on the distance from the GNSS antenna to the CLP and on the repeatability of the zero shift of the accelerometers are shown in Figs. 2-5. The dotted line in the figures indicates the permissible RMS when performing automatic landing in accordance with category III.

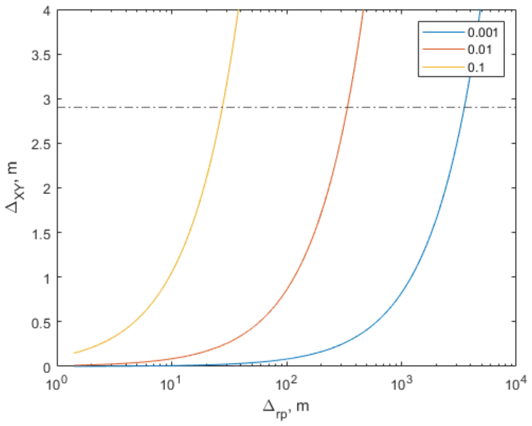


Fig. 2. RMS coordinates in the LLF depending on the distance from the CLP to the GNSS PCA in the plane of the landing platform.

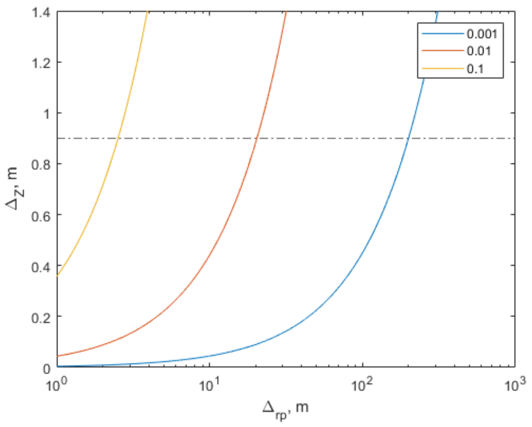


Fig. 3. RMS of the height in the LLF depending on the distance from the CLP to the GNSS PCA in the plane of the landing platform

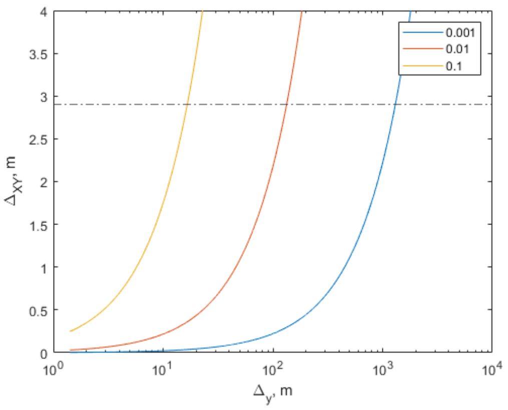


Fig. 4. RMS coordinates in the LLF depending on the distance from the CLP to the PCA GNSS normal to the plane of the landing platform.

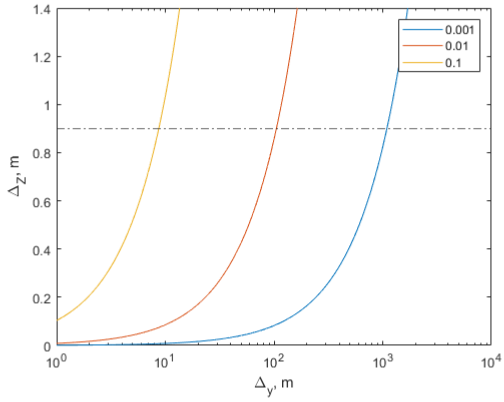


Fig. 5. RMS of the height in the LLF depending on the distance from the CLP to the PCA GNSS normal to the plane of the landing platform.

According to the graphs in Figs. 2-5, it is possible to determine the minimum required accuracy of the sensors in terms of the cumulative random drift of zero value, depending on the placement of the GNSS antenna on the landing platform.

Conclusion

The errors of determining the aircraft location in the GNSS landing system on a mobile platform when using MEMS accelerometers of different accuracy classes to stabilize the landing glide path have been determined.

The requirements for MEMS sensors are given to minimize the impact of platform mobility on the accuracy characteristics of the GNSS landing system.

The results obtained can be used to develop recommendations on the placement of the GNSS antenna and the choice of MEMS accelerometers to ensure the specified requirements for the accuracy of locations when constructing a GNSS landing system for a mobile platform.

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