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TEMPERATURE CALIBRATION OF NAVIGATIONAL ACCELEROMETER UNIT

Ua Розглянуто спосіб температурного калібрування трьохосного блока навігаційних акселерометрів за допомогою кантувача. Отримані поліноміальна та кусково-лінійна моделі температурних похибок. Запропоновані шляхи алгоритмічної компенсації температурних похибок. Експериментально підтверджено адекватність розробленого способу температурного калібрування блоку навігаційних акселерометрів.

Ru Рассмотрен способ температурной калибровки трехосного блока навигационных акселерометров с помощью кантователя. Получены полиномиальная та кусочно-линейная модели температурных погрешностей. Предложенные пути алгоритмической компенсации температурных погрешностей. Экспериментально подтверждена адекватность разработанного способа температурной калибровки блока навигационных акселерометров.

Introduction

Navigational accelerometer unit (AU) includes three linear accelerometers (AC), each accelerometer measuring axis (MA) is collinear to AU MA. AU transforms three imaginary accelerate projections of the base to AC output normalized electrical signals [1]. These projections are calculated by the consumer using AU metrological model (MM) [1], therefore projections are considered to be AU measurement results. Accordingly, MM describes the dependence between desired projections and each AU AC output electric signal. MM coefficients are identified by AU calibration.

AU measurement error is the subtraction between these measurement results and true value of desired acceleration projections. The origin of AU temperature errors is the change of its temperature to calibration temperature. Temperature errors are systematic errors, thus they depend on temperature changes and measurement results [2], [3]. These errors will reduce AU measurement accuracy, if temperature error correction is not done.

Under AU temperature calibration we will understand the process of identification and certification temperature coefficients of AU temperature error model in the operating temperature range. Temperature calibration is performed for further algorithmic compensation of AU temperature errors.

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AU temperature calibration is not almost considered in literature. Nowadays for AU temperature errors (TE) compensation only temperature calibration results of each AC, which are part of AU [3, 4] are used. This significantly limits the accuracy of algorithmic compensation AU TE, because of not counted cross-axis sensitivity between accelerometer measurement axes.

Meanwhile, questions of AU calibration in normal conditions were considered in the literature, in particular for biaxial [5] and simple uniaxial [1] rotary stands. Due to authors research in article [1] the AU calibration accuracy largely depends on the quality of AU reset on the stand platform. The easiest way of AU calibration proposed in [1], can be applied to AU temperature calibration (in case of location the turntable stand in heat chamber). However it is necessary to carry out the above mentioned precision AU reset directly in heat chamber at sufficiently high (low) temperatures, which practically is very difficult.

Problem statement

The purpose of the article is to develop the method of AU temperature calibration using special device – tilt, which excludes AU reset in temperatures and allows performing calibration by one-time passage at all calibration temperatures, and also experimental verification of temperature calibration quality and comparison of two algorithmic compensation methods of AU temperature errors after temperature calibration.

Metrological model of accelerometer unit

We assume that AU measurement results determination is carried out by its MM, which carefully described in work [1]. Herewith, we assume that AU appearance, MA orientation relative to accelerometer MA installed in AU are the same as shown in fig. 1 of the article [1].

Then linear output signal MM of this AU has the form

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} U_{0x} \\ U_{0y} \\ U_{0z} \end{bmatrix}, \qquad (1)$$

where – accelerometers output signals; a_x, a_y, a_z – measurable acceleration projections on AU MA; $K_{ii}(i = x, y, z)$ – gain coefficients (G); $K_{ij}(i, j = x, y, z, i \neq j)$ – cross-axis sensitivity coefficients (CAS); U_{0x}, U_{0y}, U_{0z} – zero g offset (ZGO).

Calculation of required acceleration projections on AU MA (AU measurement results) is accomplished by the model

$$\begin{bmatrix} \hat{a}_x \\ \hat{a}_y \\ \hat{a}_z \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}^{-1} \begin{bmatrix} \hat{U}_x - U_{0x} \\ \hat{U}_y - U_{0y} \\ \hat{U}_z - U_{0z} \end{bmatrix} = \begin{bmatrix} N_{xx} & N_{xy} & N_{xz} \\ N_{yx} & N_{yy} & N_{yz} \\ N_{zx} & N_{zy} & N_{zz} \end{bmatrix} \begin{bmatrix} \hat{U}_x - U_{0x} \\ \hat{U}_y - U_{0y} \\ \hat{U}_z - U_{0z} \end{bmatrix}, \qquad (2)$$

where $N_{ii}(i = x, y, z)$ – inverse gain coefficients; $N_{ij}(i, j = x, y, z; i \neq j)$ – inverse cross-axis sensitivity coefficients.

Twelve coefficients $K_{ii}(i = x, y, z)$, $K_{ij}(i, j = x, y, z, i \neq j)$, $U_{0i}(i = x, y, z)$ of these models are AU individual metrological coefficients (passport constants), numerical values of which are determined by AU calibration.

If in operation the temperature, at which the measurement was made by AU, is different from calibration temperature, numerical values of these twelve coefficients will be changed, that is the origin of AU temperature errors.

Accelerometer unit temperature errors model

Under the AU temperature errors model we will understand the mathematical formulas for their calculating according to twelve passport constants of MM (1) defined at normal temperature of its calibration, measurement results of accelerometer output signals, changing of operating temperature relative to calibration temperature and temperature coefficients of AU MM twelve passport constants, which so far are unknown and should be determined by AU temperature calibration results.

For getting the AU temperature errors expressions, firstly we find the AU absolute measurement errors. Using model (2) for this we find absolute error of system (2) vector-column $\hat{a}_i$, provided that small changes of ΔK_{ij} matrix elements K_{ij} and ΔU_{0i} elements of the model (1) vector-column U_{0i} $(i, j = x, y, z)$ appeared. Originally we find expressions for elements of inverse matrix $N = K^{-1}$, then we find complete differential of right side of equation (2), namely the dependence $\Delta a_i \approx da_i = \varphi_1(\Delta N_{ij}, \Delta U_{0i})$, and determine differential $\Delta N_{ij} = \varphi_2(\Delta K_{ij})$. Then we paste differential value ΔN_{ij} to Δa_i, and get next model of absolute instrumental measurement error of AU acceleration projections

$$\begin{pmatrix} \Delta a_x \\ \Delta a_y \\ \Delta a_z \end{pmatrix} = \begin{pmatrix} -\frac{1}{K_{xx}^2}\Delta K_{xx} & -\frac{1}{K_{xx}K_{yy}}\Delta K_{xy} & -\frac{1}{K_{xx}K_{zz}}\Delta K_{xz} \\ -\frac{1}{K_{xx}K_{yy}}\Delta K_{yx} & -\frac{1}{K_{yy}^2}\Delta K_{yy} & -\frac{1}{K_{yy}K_{zz}}\Delta K_{yz} \\ -\frac{1}{K_{xx}K_{zz}}\Delta K_{zx} & -\frac{1}{K_{yy}K_{zz}}\Delta K_{zy} & -\frac{1}{K_{zz}^2}\Delta K_{zz} \end{pmatrix} \begin{pmatrix} \hat{U}_x - U_{0x} \\ \hat{U}_y - U_{0y} \\ \hat{U}_z - U_{0z} \end{pmatrix} - \qquad (3)$$

$$-\begin{pmatrix} \frac{1}{K_{xx}} & -\frac{K_{xy}}{K_{xx}K_{yy}} & -\frac{K_{xz}}{K_{xx}K_{zz}} \\ -\frac{K_{yx}}{K_{xx}K_{yy}} & \frac{1}{K_{yy}} & -\frac{K_{yz}}{K_{yy}K_{zz}} \\ -\frac{K_{zx}}{K_{xx}K_{zz}} & -\frac{K_{zy}}{K_{yy}K_{zz}} & \frac{1}{K_{zz}} \end{pmatrix} \begin{pmatrix} \Delta U_{0x} \\ \Delta U_{0y} \\ \Delta U_{0z} \end{pmatrix}.$$

Expressions (3) are common expressions for determination systematic errors of AU measurement results, the origin of which is AU passport constants changing (for any reason). In this case, the source of this change is effect of ambient temperature changes:

$$\Delta T = T_{nom} - T_0,$$

where T_{nom}, ^{0}C – current ambient temperature at which measurement is made by AU; T_0, ^{0}C – ambient temperature at which calibration was performed, which results were used for certification above mentioned passport constants. Subsequently, temperature T_0, ^{0}C we will call "normal" (NC) temperature of AC using.

For received required expressions of AU TE we will take two types of dependencies passport constants of temperature change ΔT:

1. Polynomial type

$$\Delta U_{0i} = \alpha_{1i}\Delta T + \alpha_{2i}\Delta T^2 + \alpha_{3i}\Delta T^3 + \ldots + \alpha_{ki}\Delta T^k = \sum_{n=1}^{k}\alpha_{ni}\Delta T^n,$$

$$\Delta K_{ii} = K_{ii}(\beta_{1ii}\Delta T + \beta_{2ii}\Delta T^2 + \beta_{3ii}\Delta T^3 + \ldots + \beta_{kii}\Delta T^k) = K_{ii}\sum_{n=1}^{k}\beta_{nii}\Delta T^n, \quad (4)$$

$$\Delta K_{ij} = K_{ij}(\gamma_{1ij}\Delta T + \gamma_{2ij}\Delta T^2 + \gamma_{3ij}\Delta T^3 + \ldots + \gamma_{kij}\Delta T^k) = K_{ij}\sum_{n=1}^{k}\gamma_{nij}\Delta T^n,$$

where $k = 1 \ldots K$ – polynomial order; $n = 1 \ldots k$; α_{1i}, α_{2i}, α_{3i} $\left[V/{^\circ C^k}\right]$, β_{1ii}, β_{2ii}, β_{3ii} $\left[1/{^\circ C^k}\right]$, γ_{1ij}, γ_{2ij}, γ_{3ij} $\left[1/{^\circ C^k}\right]$ – appropriate linear, quadratic, cubic ZGO, G, CAS temperature coefficients;

2. Piecewise linear type

$$\Delta U_{0il} = \alpha_{il}\Delta T, \quad \Delta K_{iil} = K_{ii_{кал}}\beta_{ii_l}\Delta T, \quad \Delta K_{ijl} = K_{ij_{кал}}\gamma_{ij_l}\Delta T, \quad (5)$$

where $m = 1 \ldots M$ – number of temperature ranges in the temperature range; $l = 1 \ldots m$; α_{il} $\left[V/{^\circ C}\right]$, β_{ii_l} $\left[1/{^\circ C}\right]$, γ_{ij_l} $\left[1/{^\circ C}\right]$ – appropriate linear ZGO, G, CAS temperature coefficients for each interval; ΔU_{0il}, ΔK_{iil}, ΔK_{ijl} – appropriate ZGO, G, CAS changes for each interval.

Accordingly, for AU TE polynomial and piecewise linear models we will paste expressions (4) and (5) to formula (3). After transformation total AU TE polynomial model (of any order) represented as following

$$\Delta a_{iT} = \sum_{n=1}^{k}\left(-\frac{(\hat{U}_i - U_{0i})}{K_{ii}}\beta_{nii} - \sum_{j\neq i}^{2}\frac{(\hat{U}_j - U_{0j})}{K_{ii}K_{jj}}K_{ij}\gamma_{nij} - \frac{\alpha_{ni}}{K_{ii}} + \sum_{j\neq i}^{2}\frac{K_{ij}\alpha_{nj}}{K_{ii}K_{jj}}\right)\Delta T^n . \quad (6)$$

Similarly AU TE piecewise linear model can be define by next formulas

$$\Delta a_{iT} = \left(-\frac{(\hat{U}_i - U_{0i_{кал}})}{K_{ii_{кал}}}\beta_{ii_l} - \sum_{j\neq i}^{2}\frac{(\hat{U}_j - U_{0j_{кал}})}{K_{ii_{кал}}K_{jj_{кал}}}K_{ij_{кал}}\gamma_{ij_l} - \right.$$
$$\left. - \frac{\alpha_{i_l}}{K_{ii_{кал}}} + \sum_{j\neq i}^{2}\frac{K_{ij_{кал}}\alpha_{j_l}}{K_{ii_{кал}}K_{jj_{кал}}}\right)\Delta T , \quad (7)$$

where $K_{ii_{кал}}$, $K_{jj_{кал}}$, $K_{ij_{кал}}$, $U_{0i_{кал}}$, $U_{0j_{кал}}$ – calibration passport constants identified at temperature $T=T_{н.у.}$

Common expressions (6) and (7) can be simplified (for their easier practical use), thus we will neglect second and fourth components of these equations, which have greater order of smallness than the first and the third components. This is possible because CAS values are substantially (by 2 orders) less than G value for today's AU. The result is AU TE simplified model:

1. Polynomial

$$\Delta a_{iT} = \sum_{n=1}^{k}\left(-\frac{(\hat{U}_i - U_{0i})}{K_{ii}}\beta_{nii} - \frac{\alpha_{ni}}{K_{ii}}\right)\Delta T^n ; \quad (8)$$

2. Piecewise linear

$$\Delta a_{iT} = \left(-\frac{(\hat{U}_i - U_{0i_{кал}})}{K_{ii_{кал}}}\beta_{ii_l} - \frac{\alpha_{i_l}}{K_{ii_{кал}}}\right)\Delta T . \quad (9)$$

Expressions (6), ..., (9) allow to calculate numerical values of AU temperature errors, if we know its passport constants, numerical value of temperature changes, which determined by AU thermocouple results, and appropriate ZGO, G, CAS temperature coefficients, which so far are unknown and will be determined after AU temperature calibration.

The method of temperature calibration

Due to the proposed in the article [1] AU calibration method, where AU set at platform of uniaxial rotary stand (URS), with the help of the stand we can set in eight AU test positions (TP1 … TP8) relative to local horizon plane (LHP). Herewith AU should be reset two times on URS platform. Authors of the article [1] assert that this AU reset is major source of errors, and it is fundamentally impossible at large positive or negative temperatures.

We will use special device – tilt to avoid these problems in setting AU in test positions, tilt performs the same function as uniaxial stand. Tilt, which is shown in fig. 1, has seven basic surfaces $S1 \div S7$. Each test position (TP) is shown in fig. 2.

This tilt allows setting only six AU test positions (TP1 ... TP6) relative to LHP, so mathematical model of AU calibration, which was proposed in work [1], should be modified to model with six TP.

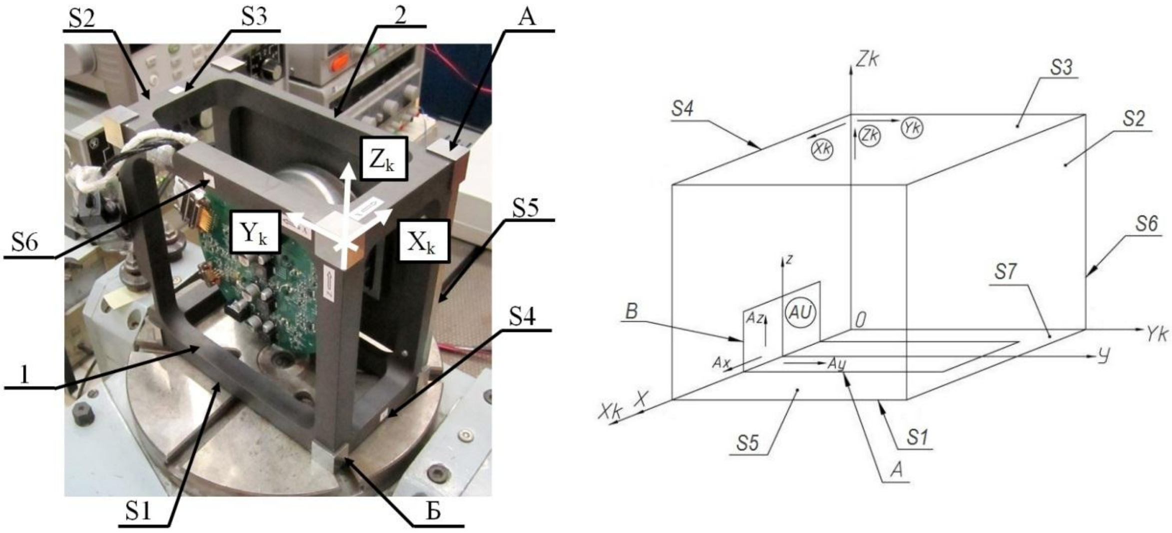

Fig. 1. AU set in tilt: 1 – tilt, 2 - AU, $OX_kY_kZ_k$ – coordinates system associated with tilt, OXYZ – coordinates system associated with AU, which is set in tilt inner surface (S7)

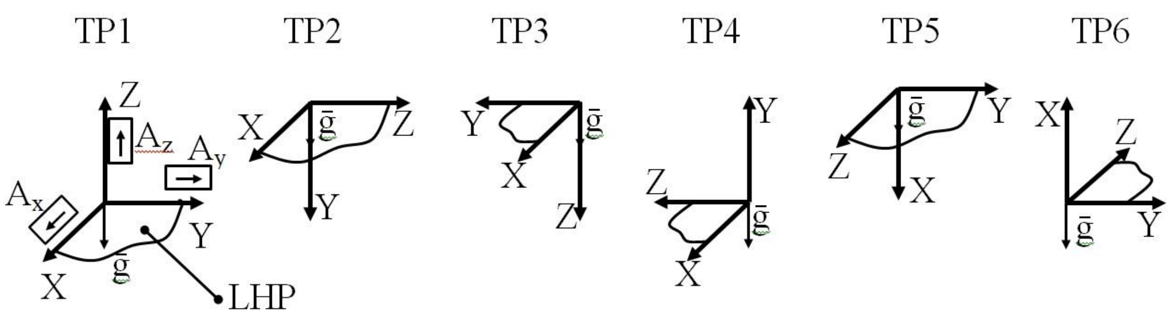

Fig. 2. Scheme of AU TP, which are set in its calibration by tilt

According to fig. 2 and AU calibration method, proposed in the article [1], projections of $\vec{g}$ vector to AU MA in each TP are known, also its output signals should be determined for each TP by model (1) (18 expressions). As an example, expressions for AU output signals in TP2 and TP4 are presented below

$$\begin{cases} U_{x2} = -K_{xy} g + U_{0x} \\ U_{y2} = -K_{yy} g + U_{0y} \\ U_{z2} = -K_{zy} g + U_{0z} \end{cases}, \qquad \begin{cases} U_{x4} = K_{xy} g + U_{0x} \\ U_{y4} = K_{yy} g + U_{0y} \\ U_{z4} = K_{zy} g + U_{0z} \end{cases}. \tag{10}$$

Having examined relevant linear combinations of eighteen AU output signals expressions, by procedure in the article [1] we obtain the following formulas for determination all AU MM 12 coefficients:

$$K_{xx}=\frac{U_{x6}-U_{x5}}{2g}\left[V/g\right];\quad K_{xy}=\frac{U_{x4}-U_{x2}}{2g}\left[V/g\right];\quad K_{xz}=\frac{U_{x1}-U_{x3}}{2g}\left[V/g\right];$$

$$K_{yx}=\frac{U_{y6}-U_{y5}}{2g}\left[V/g\right];\quad K_{yy}=\frac{U_{y4}-U_{y2}}{2g}\left[V/g\right];\quad K_{yx}=\frac{U_{y1}-U_{y3}}{2g}\left[V/g\right];$$

$$K_{zx}=\frac{U_{z6}-U_{z5}}{2g}\left[V/g\right];\quad K_{zy}=\frac{U_{z4}-U_{z2}}{2g}\left[V/g\right];\quad K_{zz}=\frac{U_{z1}-U_{z3}}{2g}\left[V/g\right]; \tag{11}$$

$$U_{0x}=\frac{1}{4}(U_{x1}+U_{x2}+U_{x3}+U_{x4})\,[V];\qquad U_{0y}=\frac{1}{4}(U_{y1}+U_{y2}+U_{y5}+U_{y6})\,[V];$$

$$U_{0z}=\frac{1}{4}(U_{z2}+U_{z4}+U_{z5}+U_{z6})\,[V],$$

where $U_{xi}(i=1,...,6)$, $U_{yi}(i=1,...,6)$, $U_{zi}(i=1,...,6)$ – AU AC output signals in six test positions (TP1 ... TP6).

Determining AU MM coefficients should be done on each test calibration temperature. The number of test temperatures is determined by the number of piecewise linear model subbands of its TE or by order polynomial model of TE. That is $s=k+1$ or $s=m+1$, where s –number of test temperatures (including normal temperature $T_{\text{н.у.}}$).

So for determination of desired temperature coefficients of MM AU twelve coefficients for the most common third-order polynomial model we need to form three equations system (for ΔU_{0i}, ΔK_{ii}, ΔK_{ij}) by model (4), each of which will have three equations relatively ΔT (according to selected third-order polynomial). Solution of these systems by Cramer's rule [6] allows to get the following formulas for desired AU ZGO, G and CAS temperature coefficients

$$\alpha_{1i}=\frac{\Delta_{1\alpha}}{\Delta},\quad \alpha_{2i}=\frac{\Delta_{2\alpha}}{\Delta},\quad \alpha_{3i}=\frac{\Delta_{3\alpha}}{\Delta},\quad \beta_{1ii}=\frac{\Delta_{1\beta}}{\Delta},\quad \beta_{2ii}=\frac{\Delta_{2\beta}}{\Delta},$$
$$\beta_{3ii}=\frac{\Delta_{3\beta}}{\Delta},\quad \gamma_{1ij}=\frac{\Delta_{1\gamma}}{\Delta},\quad \gamma_{2ij}=\frac{\Delta_{2\gamma}}{\Delta},\quad \gamma_{3ij}=\frac{\Delta_{3\gamma}}{\Delta}, \tag{12}$$

where $\Delta=\begin{vmatrix}\Delta T_{н} & \Delta T_{н}^{2} & \Delta T_{н}^{3}\\ \Delta T_{в} & \Delta T_{в}^{2} & \Delta T_{в}^{3}\\ \Delta T_{сн} & \Delta T_{сн}^{2} & \Delta T_{сн}^{3}\end{vmatrix}$ - main system determinant;

$$\Delta_{1\alpha} = \begin{vmatrix} U_{0i_н} - U_{0i_{кал}} & \Delta T_н^2 & \Delta T_н^3 \\ U_{0i_в} - U_{0i_{кал}} & \Delta T_в^2 & \Delta T_в^3 \\ U_{0i_{сн}} - U_{0i_{кал}} & \Delta T_{сн}^2 & \Delta T_{сн}^3 \end{vmatrix},$$

$$\Delta_{2\alpha} = \begin{vmatrix} \Delta T_н & U_{0i_н} - U_{0i_{кал}} & \Delta T_н^3 \\ \Delta T_в & U_{0i_в} - U_{0i_{кал}} & \Delta T_в^3 \\ \Delta T_{сн} & U_{0i_{сн}} - U_{0i_{кал}} & \Delta T_{сн}^3 \end{vmatrix},$$

$$\Delta_{3\alpha} = \begin{vmatrix} \Delta T_н & \Delta T_н^2 & U_{0i_н} - U_{0i_{кал}} \\ \Delta T_в & \Delta T_в^2 & U_{0i_в} - U_{0i_{кал}} \\ \Delta T_{сн} & \Delta T_{сн}^2 & U_{0i_{сн}} - U_{0i_{кал}} \end{vmatrix}, \ \Delta_{1\beta} = \begin{vmatrix} K_{ii_н} - K_{ii_{кал}} & \Delta T_н^2 & \Delta T_н^3 \\ K_{ii_в} - K_{ii_{кал}} & \Delta T_в^2 & \Delta T_в^3 \\ K_{ii_{сн}} - K_{ii_{кал}} & \Delta T_{сн}^2 & \Delta T_{сн}^3 \end{vmatrix},$$

$$\Delta_{2\beta} = \begin{vmatrix} \Delta T_н & K_{ii_н} - K_{ii_{кал}} & \Delta T_н^3 \\ \Delta T_в & K_{ii_в} - K_{ii_{кал}} & \Delta T_в^3 \\ \Delta T_{сн} & K_{ii_{сн}} - K_{ii_{кал}} & \Delta T_{сн}^3 \end{vmatrix}, \Delta_{3\beta} = \begin{vmatrix} \Delta T_н & \Delta T_н^2 & K_{ii_н} - K_{ii_{кал}} \\ \Delta T_в & \Delta T_в^2 & K_{ii_в} - K_{ii_{кал}} \\ \Delta T_{сн} & \Delta T_{сн}^2 & K_{ii_{сн}} - K_{ii_{кал}} \end{vmatrix},$$

$$\Delta_{1\gamma} = \begin{vmatrix} K_{ij_н} - K_{ij_{кал}} & \Delta T_н^2 & \Delta T_н^3 \\ K_{ij_в} - K_{ij_{кал}} & \Delta T_в^2 & \Delta T_в^3 \\ K_{ij_{сн}} - K_{ij_{кал}} & \Delta T_{сн}^2 & \Delta T_{сн}^3 \end{vmatrix}, \Delta_{2\gamma} = \begin{vmatrix} \Delta T_н & K_{ij_н} - K_{ij_{кал}} & \Delta T_н^3 \\ \Delta T_в & K_{ij_в} - K_{ij_{кал}} & \Delta T_в^3 \\ \Delta T_{сн} & K_{ij_{сн}} - K_{ij_{кал}} & \Delta T_{сн}^3 \end{vmatrix},$$

$$\Delta_{3\gamma} = \begin{vmatrix} \Delta T_н & \Delta T_н^2 & K_{ij_н} - K_{ij_{кал}} \\ \Delta T_в & \Delta T_в^2 & K_{ij_в} - K_{ij_{кал}} \\ \Delta T_{сн} & \Delta T_{сн}^2 & K_{ij_{сн}} - K_{ij_{кал}} \end{vmatrix}$$

– determinants of these systems, which are formed by the main determinant and corresponding replacements.

For determination desired temperature coefficients $\alpha_i, \beta_{ii}, \gamma_{ij}$ of AU TE simple piecewise linear model (with two temperature subbands) the following simple expressions are used:

$$\alpha_{iн} = \frac{U_{0i_н} - U_{0i_{кал}}}{T_н - T_0}; \quad \beta_{iiн} = \frac{K_{ii_н} - K_{ii_{кал}}}{K_{ii_{кал}}(T_н - T_0)}; \ \gamma_{ijн} = \frac{K_{ijн} - K_{ij_{кал}}}{K_{ij_{кал}}(T_н - T_0)},$$
$$\Delta T \le 0;$$
$$\alpha_{iв} = \frac{U_{0i_в} - U_{0i_{кал}}}{T_в - T_0}; \quad \beta_{iiв} = \frac{K_{ii_в} - K_{ii_{кал}}}{K_{ii_{кал}}(T_в - T_0)}, \quad \gamma_{ijв} = \frac{K_{ijв} - K_{ij_{кал}}}{K_{ij_{кал}}(T_в - T_0)},$$
$$\Delta T \ge 0. \tag{13}$$

Compensation ways for accelerometer unit temperature errors

Relevant AU ZGO, G and CAS temperature coefficients, obtained by proposed method, are used for further algorithmic compensation AU TE that can be accomplished by the following methods [2] as well as for any mechanical quantities transducer:

- mathematical method of correction AU MM passport constants current values based on current temperature T_{nom}, at which AU measures, and besides corrective applications are changes of ZGO, G and CAS coefficients, which are determined by formulas (4);
- method of calculating values of its absolute systematic temperature errors for current temperature T_{nom}, and subsequent correction of AU measurement results by introducing amendments to these measurement results, which are determined by formulas (3) and (4), i.e.

$$a_{\kappa i} = a_i - \Delta a_{iT},$$

where $a_{\kappa i}$ – adjusted value of acceleration projections at AU MA considering temperature changes; a_i – AU measurement results, which are determined by formula (2) using MM passport constants, are defined at temperature $T=T_{н.у.}$; Δa_{iT} – numerical value of AU absolute systematic temperature errors, which are calculated by formulas (3), ..., (5).

Experimental quality verification of accelerometer unit temperature calibration

Experimental quality verification of AU temperature calibration using tilt is performed by comparing measurement errors of gravity acceleration module [1] at verification temperatures, the conditions for comparing:

- measurement errors of gravity acceleration module with correction AU MM coefficients by formulas (4) or (5), and without correction;
- measurement errors of gravity acceleration module with correction AU TE by formulas (6) or (7), and without correction.

These errors are determined by the following formula, which is described in the article [1]

$$\Delta g_i = g_{pi} - g_И \le \Delta g_Д, \qquad [g] \qquad (14)$$

where $g_{pm} = \sqrt{a_{xm}^2 + a_{ym}^2 + a_{zm}^2}$ – calculated by AU measurement results value of vector $\vec{g}$ module; $\Delta g_Д$ – tolerance level of measurement error vector $\vec{g}$ module at normal temperature for ensuring AU specified accuracy.

For example, calibration will be done efficiently for AU in strapdown inertial navigation system of carrier rocket (type "Cyclone-4"), if calibration is achieved at normal temperature with $\Delta g_Д \approx \pm 3 \cdot 10^{-4} g$, and in operating temperatures range with $\Delta g_Д \approx \pm 10 \cdot 10^{-4} g$.

Stand equipment, required for AU temperature calibration and developed by the above mentioned method, is shown in fig. 3 and described in detail in the article [1] (except tilt that is shown in fig. 1).

Comparison of these errors was made by method in work [1] in six verification positions (VP1...VP6) of tilt with AU, which are shown in fig. 4. For example, in fig. 5 tilt with AU installed in VP1 is shown.

Voltmeter measures each AU AC output signals in these positions for further calculation of AU MM coefficients (1) at verification temperatures ($T_{н.у.}$=+20°C, $T_н$=-40°C, $T_в$=+70°C), and for calculation unknown errors, which are compared.

Calculating results of AU MM coefficients by formulas (11) at calibration temperatures are presented in table 1 and table 2. Comparison of coefficients numerical values shows that they depend on the temperature calibration.

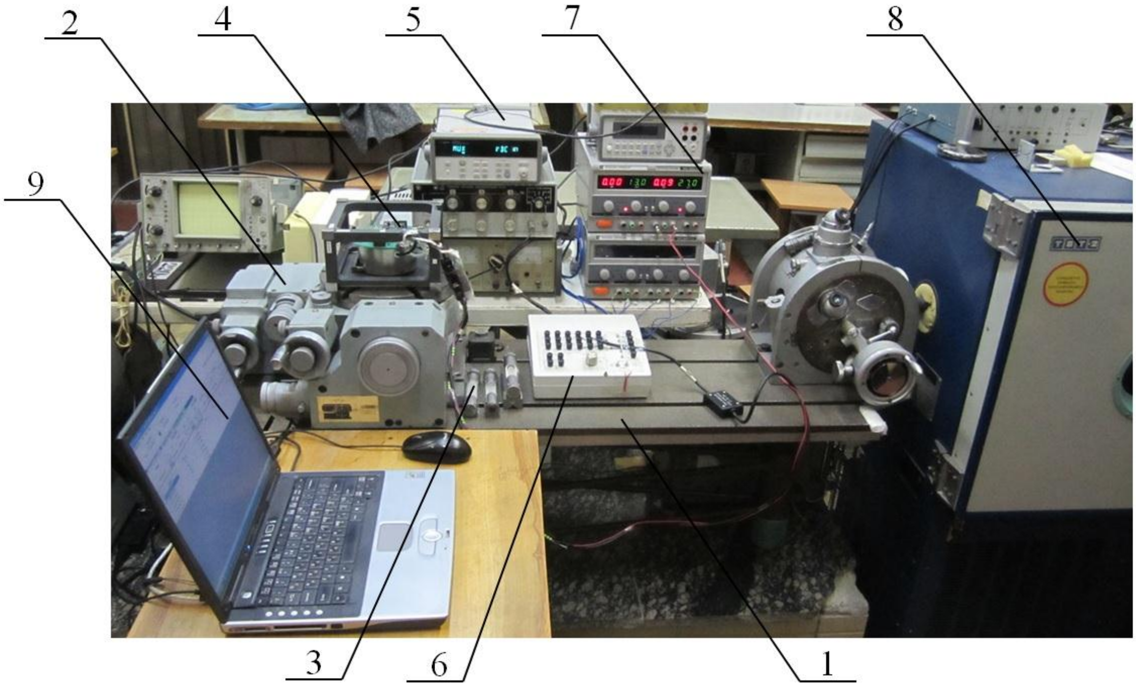

Fig. 3. Stand for AU temperature calibration: 1 – foundation, 2 – two-axis local horizon platform, 3 – bubble level, 4 – tilt with AU, 5 – precision voltmeter, 6 – control unit, 7 – power supply, 8 - heat chamber, 9 – computer

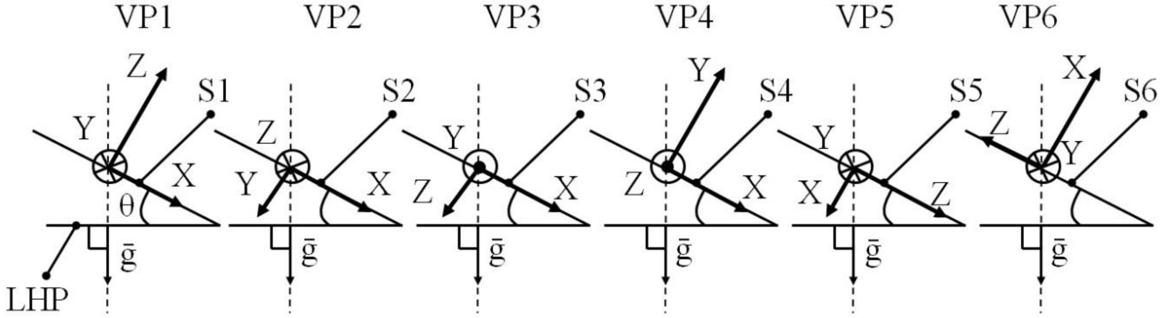

Fig. 4. Scheme of AU (set in tilt) VP, which are set for verification of calibration using tilt

Then, temperature coefficients of piecewise linear model (7) with two temperature subbands were calculated using coefficients numerical values, which are determined by the results of AU temperature calibration. Temperature coefficients are listed in the table 3.

Using the above mentioned coefficients for verification temperatures T=-10°C ;+45°C numerical values of AU MM passport coefficients were corrected by formulas (5), and were calculated additional AU TE by formulas (7).

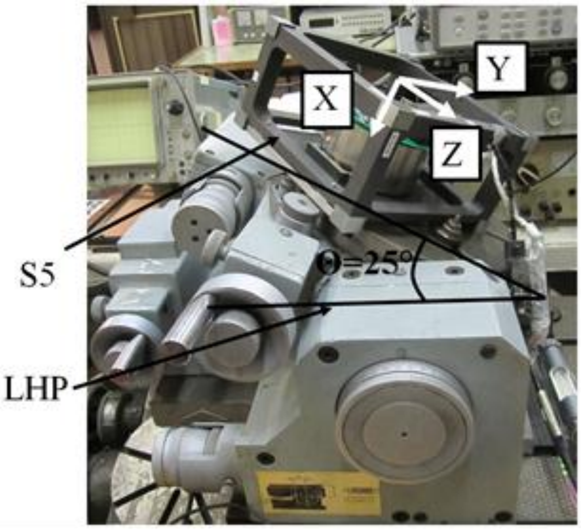

Fig. 5. AU set in tilt in VP 5

***Table* 1.**

AU MM G and ZGO values at $T_{н.у.}$=+20°C, $T_{н}$=-40°C, $T_{в}$=+70°C

Tempera-ture	**G,** B/g			**ZGO,** B		
	K_{xx}	K_{yy}	K_{zz}	U_{0x}	U_{0y}	U_{0z}
$T=T_{н.у.}$=+20°C	-0,55060863	-0,54854890	-0,54859224	0,00449084	-0,00442299	-0,00347099
$T=T_{н}$=-40°C	-0,55074263	-0,54790681	-0,54832201	0,01181219	0,00057544	0,00041269
$T=T_{в}$=+70°C	-0,55140269	-0,54933059	-0,54979681	0,00359778	-0,00643609	-0,00223732

***Table* 2.**

AU MM CAS values at $T_{н.у.}$=+20°C, $T_н$=-40°C, $T_в$=+70°C

Tempera-ture	**CAS,** B/g					
	K_{xy}	K_{xz}	K_{yx}	K_{yz}	K_{zx}	K_{zy}
$T=T_{ну}$=+20°C	-0,00051742	0,01639328	-0,01322881	-0,00066841	-0,01466957	-0,00035441
T=Tн=-40°C	-0,00038930	0,01602241	-0,01277214	-0,00074432	-0,01433019	-0,00023161
T=Tв=+70°C	-0,00042829	0,01652937	-0,01364519	-0,00068396	-0,01478830	-0,00027167

***Table* 3.**

AU MM ZGO $\alpha_{1i}(i=x,y,z)$, G $\beta_{1ii}(i=x,y,z;i=j)$ and CAS $\gamma_{1ij}(i,j=x,y,z;i\neq j)$ temperature coefficients values for piecewise linear model with two temperature subbands

AU MM temperature coefficient	**Symbol**	**Value in range from -40°C to +20°C**	**Value in range from +20°C to +70°C**
G temperature coefficient, $\beta_{1ii}(i=x,y,z;i=j)$ $\lfloor 1/°C \rfloor$	β_{1xx}	-0,00000406	0,00002884
	β_{1yy}	0,00001951	0,00002850
	β_{1zz}	0,00000821	0,00004391
ZGO temperature coefficient, $\alpha_{1i}(i=x,y,z)$, $\lfloor V/°C \rfloor$	α_{1x}	-0,00012202	-0,00001786
	α_{1y}	-0,00008331	-0,00004026
	α_{1z}	-0,00006473	0,00002467
CAS temperature coefficient of Ax canal, $\lfloor 1/°C \rfloor$	γ_{1xy}	0,00412678	-0,00344515
	γ_{1xz}	0,00037706	0,00016603
CAS temperature coefficient of Ay canal, $\lfloor 1/°C \rfloor$	γ_{1yx}	0,00057535	0,00062950
	γ_{1yz}	-0,00189274	0,00046547
CAS temperature coefficient of Az canal, $\lfloor 1/°C \rfloor$	γ_{1zx}	0,00038558	0,00016187
	γ_{1zy}	0,00577492	-0,00466918

Algorithmic compensation has been made using the results of these calculations by two above mentioned methods (mathematical method of correction AU MM passport constants current values based on current temperature and method of introducing amendments to AU measurement results, values of which are equal to TE values). Remaining errors after algorithmic compensation are required errors for comparison. Comparison results are presented in fig. 6 and fig. 7.

Obtained experimental results show that AU TE algorithmic compensation for most simple piecewise linear model with two temperature subbands by method 1 and 2 reduce measurement error of gravity acceleration by 3-4 times. These methods provide almost the same result, however after this simplest AU TE algorithmic compensation in operating temperature range AU temperature errors are still quite large (about 4 times higher than calibration).

For reducing AU temperature errors even several times, you need to perform algorithmic compensation with complicated TE models, i.e. use more subbands of piecewise linear model (5) or use larger order of polynomial model (4) for calculation current temperature coefficients.

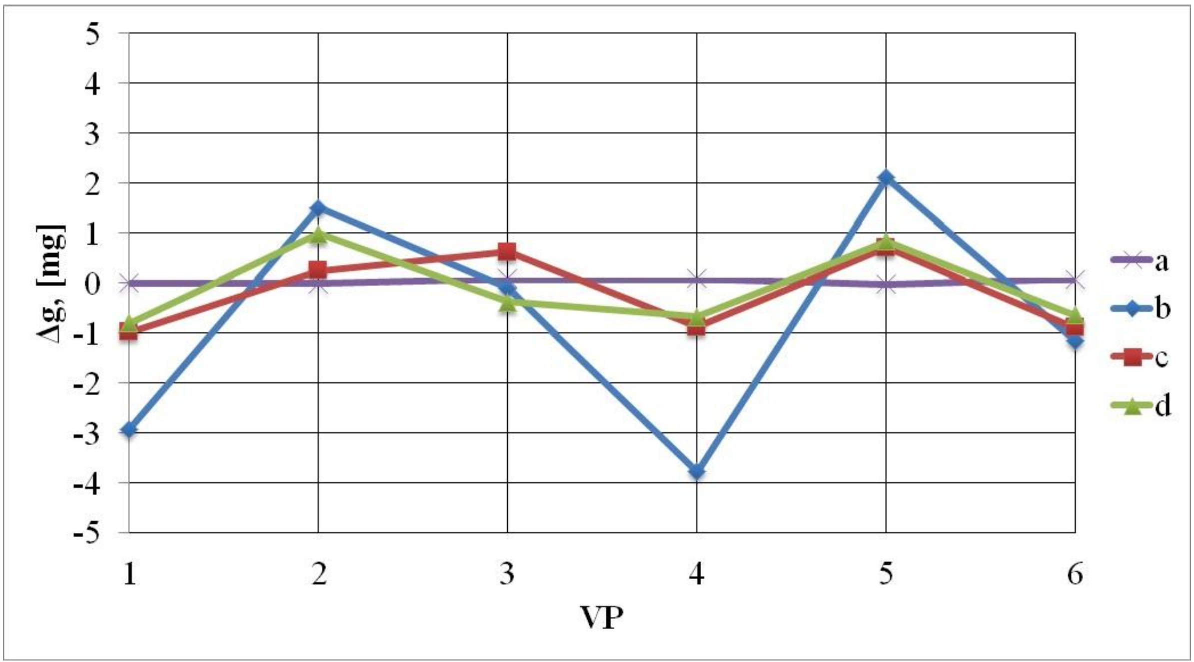

Fig. 6. Measurement errors of gravity acceleration module in verification positions (VP1 ... VP6):
line a) at $T=T_{н.у.}=+20°C$ with calibration MM coefficients, which are determined at $T=T_{н.у.}=+20°C$ (error does not exceed ± 0,12mg),
line b) - at T=-10°C in accordance with calibration MM coefficients, determined at $T=T_{н.у.}=+20°C$ without algorithmic compensation (error up to ± 4mg),
line c) - defined errors by 1 algorithmic compensation method,
line d) - defined errors by 2 algorithmic compensation method

Conclusions

It is confirmed that proposed method of AU temperature calibration using tilt provides identification all models (6) or (7) temperature coefficients by expressions (12) or (13) without AU reset and performing calibration one-time passage at all calibration temperatures.

Experimental quality verification of AU temperature calibration shows that temperature coefficients of AU MM twelve passport constants (1) were determined correctly by formulas (12) and (13), and TE algorithmic compensation by two proposed methods in the article (by using simple piecewise linear model) gives almost the same result - reducing AU temperature errors by 3-4 times, this indicates its high efficiency.

For increasing compensation accuracy it is necessary to use complex AU temperature errors models (6) and (7), or increase the number of piecewise linear model subbands (4) and polynomial model order (5).

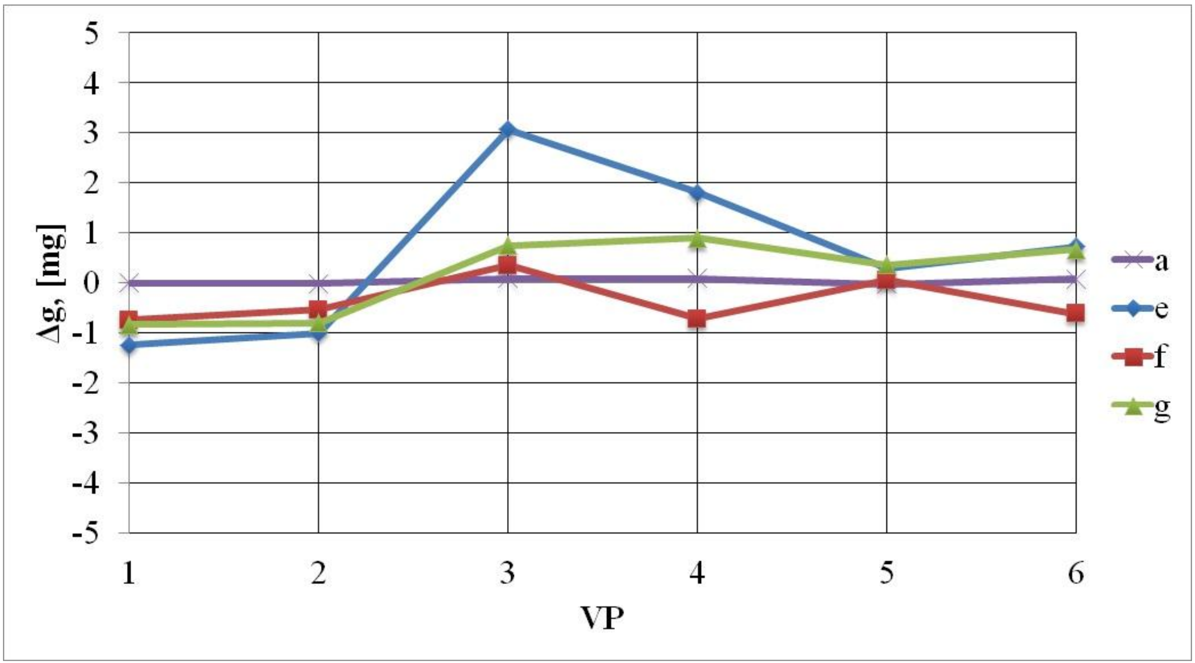

Fig. 7. Measurement errors of gravity acceleration module in verification positions (VP1...VP6):
line a) at $T=T_{н.у.}=+20°C$ with calibration MM coefficients, determined at $T=T_{н.у.}=+20°C$ (error does not exceed ± 0,12mg),
line e) - at T=+45°C with calibration MM coefficients, determined at $T=T_{н.у.}=+20°C$ (error up to ± 3mg),
line f) - defined errors by 1 algorithmic compensation method,
line g) - defined errors by 2 algorithmic compensation method

References

1. *Черняк, М. Г.* Спосіб калібрування тривісного блока навігаційних акселерометрів на одновісному поворотному стенді [Текст]/ М. Г. Черняк, В. А. Палюшок // Механика гироскопических систем. – 2013. – Вип. 26. – С. 5–15.
2. *Земельман, М. А.* Автоматическая коррекция погрешностей измерительных устройств [Текст] / М. А. Земельман - М.: Изд-во стандартов, 1972. –342с.
3. *Калинин, М. А.* О компенсации температурного ухода коэффициента преобразования акселерометра АЛЕ-055 [Текст]/ М. А. Калинин// Датчики и системы. – 2004. – № 2. – С. 33–35.

4. *Головач, С. В.* комплексная алгоритмическая компенсація температурного дрейфа измерительного канала трехосного акселерометра в составе БИНС [Текст]/ С. В. Головач // Вісник НТУУ "КПІ". Серія "Приладобудування". – 2015. – Вип. 50(2). – С. 27–34.
5. *Успенский, В. Б.* Метод калибровки акселерометрического измерительного модуля [Текст]/ В. Б. Успенский, М. В. Некрасова // Вестник НТУУ "КПИ". Серия Приладобудування - 2012. - Вип. 44(1). - С.15 - 23.
6. *Гантмахер, Ф. Р.* Теория матриц [Текст]/ Ф. Р. Гантмахер – М.: Наука, 2 изд., 1967. — 576 с.