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SENSOR CALIBRATION OF FLIGHT SIMULATOR MOTION SYSTEMS

КАЛІБРУВАННЯ ДАТЧИКІВ ДИНАМІЧНОГО СТЕНДУ АВІАЦІЙНОГО ТРЕНАЖЕРА

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Annotation. *Characteristics of flight simulator motion system directly affect on quality of motion cueing and, in this way, conformity of simulators to requirements. Method of calibration of both linear and angular acceleration and angular velocity sensors was developed. Developed methodology of sensor calibration ensuring the possibility of determining of motion system characteristics and, upon request, adjusting them. Approbation of the methodology on the aircraft flight simulators Il-96-300, Tu-204 and An-74TK-200 showed its efficiency.*

Keywords: *flight simulator motion system, sensor calibration.*

Introduction. According to the flight simulator requirements [1], six-degrees-of-freedom motion systems (6DOF) are a mandatory component of full flight simulators of the qualification level C and D. This is due to the requirement for motion cueing along six degrees of freedom: three translational (longitudinal, lateral, vertical) and three angular (pitch, roll, yaw). To ensure this, flight simulator cockpit is installed on 6DOF (Figure 1), whose movement creates motion cues along six degrees of freedom.

In order to meet the flight simulator requirements, a certain quality of motion cueing is required, to ensure which 6DOF characteristics are determined and, if necessary, adjustments are made to ensure that flight simulator meet the flight simulator requirements.

Motion systems have come a long way in development: from the first primitive device of Sander Thacher and Eardley Beeley in 1910 to the modern 6DOF, which scheme was proposed by Stewart [2] (Figure 2). This 6DOF has lower friction forces, lower mass of moving parts, better dynamic characteristics, a simpler design that does not limit a view through cockpit enclosure, provides ranges of linear movements of more than 1 m and angular - 25 degrees. In Ukraine, the first 6DOF as part of the flight simulator An-74TK-200 appeared in the mid-nineties of XX century. Investigations of motion system characteristics were conducted on the flight simulators Il-96-300, Tu-204 and An-74TK-200 [2 – 7].

Determining of 6DOF characteristics begins with sensor calibrations. Since the sensor calibrations is an important component of meeting the flight simulator requirements, the development of sensor calibrations methodology is an actual problem.

Figure 1 - Modern flight simulator

Method of calibration of both linear and angular acceleration and angular velocity sensors

To form the transformation operator of 6DOF movements along individual degrees of freedom into the movement of jacks, lets introduce (see Figure 2) the right coordinate system *OXYZ* connected to 6DOF, which origin point *O* is in the plane of the upper hinges $K_1K_2K_3$, and the axes *OX*, *OY* and *OZ* are parallel to the respective aircraft axes, and the normal fixed terrestrial coordinate system $O_gX_gY_gZ_g$, which origin point O_g coincides with the projection of point *O* on the plane of the 6DOF lower hinges $J_1J_2J_3J_4J_5J_6$ under the condition of jack movements equality $l_1 = l_2 = l_3 = l_4 = l_5 = l_6$, and whose axes O_gX_g, O_gY_g and O_gZ_g are parallel to the axes *OX*, *OY* and *OZ*, respectively. The angular orientation of the body coordinate system *OXYZ* is determined by the angles of roll γ, yaw ψ, and pitch ϑ.

In the scalar form, the rotation center coordinates of the jack upper hinges in the terrestrial coordinate system $O_gX_gY_gZ_g$ are described by the equations [8]:

$$x_{\text{в}k} = x + x_{\text{во}k}\cos\psi\cos\vartheta + z_{\text{во}k}(\sin\vartheta\cos\psi\sin\gamma + \sin\psi\cos\gamma);$$

$$y_{\text{в}k} = y + x_{\text{во}k}\sin\vartheta - z_{\text{во}k}\cos\vartheta\sin\gamma + Y_{\text{вп}}; \qquad (1)$$

$$z_{\text{в}k} = z - x_{\text{во}k}\cos\vartheta\sin\psi + z_{\text{во}k}(\cos\psi\cos\gamma - \sin\vartheta\sin\psi\sin\gamma), k = \overline{1,6},$$

where $Y_{вп}$ is the coordinate of the jack upper hinges along the vertical axis OY in the 6DOF initial position $Y_{вп} = \sqrt{l_{вп}^2 +}$, where $x_{нk}$, $z_{нk}$ are, respectively, the rotation center coordinates of the k-th lower hinges in the terrestrial coordinate system $O_gX_gY_gZ_g$ along the axes O_gX_g and O_gZ_g; $l_{вп}$ is the jack average length, which corresponds to the initial jack position and is equal to half the working stroke of the jack rods $l_{вп} = (l_{max} - l_{min}) / 2$, where l_{max}, l_{min} are, respectively, the jack lengths when the rod is fully extended and fully retracted, which are defined as the distances between the upper and the lower hinges in the jack direction with the rod fully extended and fully retracted.

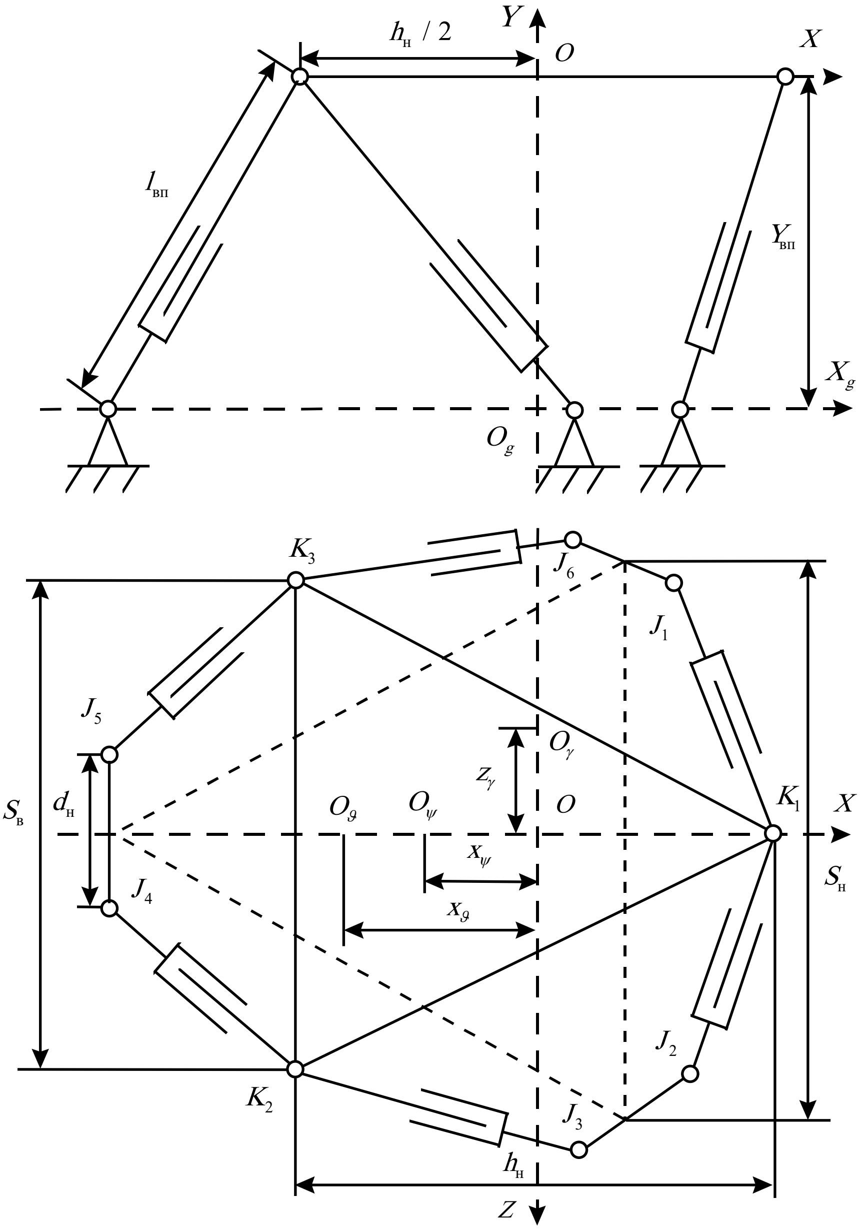

Figure 2 - Kinematic scheme of 6DOF

To determine the spatial position of the 6DOF based on the known jack displacement, equations (1) are written in the form:

$$f_{jk}(s)=\left[x+x_{\text{В}Ok}\cos\psi\cos\vartheta+z_{\text{В}Ok}(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma)-x_{\text{Н}k}\right]^2+$$
$$+(y+x_{\text{В}Ok}\sin\vartheta-z_{\text{В}Ok}\cos\vartheta\sin\gamma+Y_{\text{ВП}})^2+\left[z-x_{\text{В}Ok}\cos\vartheta\sin\psi+\right. \tag{2}$$
$$\left.+z_{\text{В}Ok}(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)-z_{\text{Н}k}\right]-\left(l_{\text{ВП}}+l_k\right)^2=0,\ k=\overline{1,6},\ j=\overline{1,6},$$

where $f_{jk}(s)$, $k=\overline{1,6}$, $j=\overline{1,6}$ are continuous functions.

To solve the system of nonlinear equations (2), which is differentiated at least once, the Newton-Kantorovich method [9] can be applied. For this, the Jacobi matrix is determined, which for the system of equations (2) is as follows:

$$f'_{1k}(x)=2[x+x_{\text{в}ok}\cos\psi\cos\vartheta+z_{\text{в}ok}(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma)-x_{\text{н}k}];$$
$$f'_{2k}(y)=2(y+x_{\text{в}ok}\sin\vartheta-z_{\text{в}ok}\cos\vartheta\sin\gamma+Y_{\text{вп}});$$
$$f'_{3k}(z)=2[z-x_{\text{в}ok}\cos\vartheta\sin\psi+z_{\text{в}ok}(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)-z_{\text{н}k}];$$
$$f'_{4k}(\gamma)=2z_{\text{в}ok}\{[x+x_{\text{в}ok}\cos\psi\cos\vartheta+z_{\text{в}ok}(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma)-x_{\text{н}k}]\times$$
$$\times(\sin\vartheta\cos\psi\cos\gamma-\sin\psi\sin\gamma)-(y+x_{\text{в}ok}\sin\vartheta-z_{\text{в}ok}\cos\vartheta\sin\gamma+Y_{\text{вп}})\times$$
$$\times\cos\vartheta\cos\gamma-[z-x_{\text{в}ok}\cos\vartheta\sin\psi+z_{\text{в}ok}(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)-$$
$$-z_{\text{н}k}](\cos\psi\sin\gamma+\sin\vartheta\sin\psi\cos\gamma)\};$$
$$f'_{5k}(\psi)=2[x+x_{\text{в}ok}\cos\psi\cos\vartheta+z_{\text{в}ok}(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma)-x_{\text{н}k}]\times$$
$$\times[z_{\text{в}ok}(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)]-[z-x_{\text{в}ok}\cos\vartheta\sin\psi+$$
$$+z_{\text{в}ok}(\cos\psi\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)-z_{\text{н}k}][x_{\text{в}ok}\cos\vartheta\cos\psi+$$
$$+z_{\text{в}ok}(\sin\psi\cos\gamma+\sin\vartheta\cos\psi\sin\gamma)];$$
$$f'_{6k}(\vartheta)=2\cos\psi[x+x_{\text{в}ok}\cos\psi\cos\vartheta+z_{\text{в}ok}(\sin\vartheta\cos\psi\sin\gamma+\sin\psi\cos\gamma)-x_{\text{н}k}]\times$$
$$\times(z_{\text{в}ok}\sin\vartheta\sin\gamma-x_{\text{в}ok}\sin\vartheta)+2(y+x_{\text{в}ok}\sin\vartheta-z_{\text{в}ok}\cos\vartheta\sin\gamma+Y_{\text{вп}})\times$$
$$\times(x_{\text{в}ok}\cos\vartheta+z_{\text{в}ok}\sin\vartheta\sin\gamma)+2\sin\psi[z-x_{\text{в}ok}\cos\vartheta\sin\psi+z_{\text{в}ok}(\cos\psi\times \tag{3}$$
$$\times\cos\gamma-\sin\vartheta\sin\psi\sin\gamma)-z_{\text{н}k}](x_{\text{в}ok}\sin\vartheta-z_{\text{в}ok}\cos\vartheta\sin\gamma),\ k=\overline{1,6}.$$

Due to the fact that the Jacobi matrix is nondegenerate, the system of nonlinear algebraic equations (3) is uniquely solved.

Calibration of linear and angular acceleration sensors. Linear and angular accelerations of 6DOF are calculated according to the formula:

$$\ddot{s}_i=\frac{\ddot{s}_{\text{д}i}-\ddot{s}_{\text{д}0}}{k_{\text{п}}}, \tag{4}$$

where $\ddot{s}_i$, $\ddot{s}_{\text{д}i}$ are, respectively, acceleration and acceleration sensor signal at the *i*-th time; $\ddot{s}_{\text{д}0}$ is average value of the acceleration sensor signals at a zero program signal: $\ddot{s}_{\text{д}0}=\frac{1}{n_0}\sum_{i=1}^{n_0}\ddot{s}_{\text{д}i}$; $k_{\text{п}}$ is calibration coefficient of acceleration sensor, which is determined by the formula obtained from (4): $k_{\text{п}}=\left(\ddot{s}_{\text{д}i}-\ddot{s}_{\text{д}0}\right)/\ddot{s}_i$.

During 6DOF movement along pitch and roll, signals of longitudinal, vertical and lateral acceleration sensors are calculated according to the corresponding formulas: $\ddot{s}_{px} = g\sin\vartheta$; $\ddot{s}_{py} = g(\cos\vartheta - 1)$; $\ddot{s}_{pz} = g\sin(-\gamma)$. To calibrate linear acceleration sensors, 6DOF is successively moved along pitch $\vartheta = f(t)$ and roll $\vartheta = f(t)$ while maintaining constant values $\vartheta = f(t)$ and $\vartheta = f(t)$, on which sensor signals of linear displacements $\{s_{дki},\ k = \overline{1,6};\ i = \overline{1,m_i}\}$ and accelerations $\{\ddot{s}_{дki},\ k = \overline{1,6};\ i = \overline{1,m_i}\}$ are registered. For this purpose, the program signal is calculated first along pitch and then along roll:

$$u_i = \begin{cases} 0 & \big|\ t_i \le t_0; t_i > 8\Delta t; \\ u_{i-1} + \Delta u \dfrac{h_t}{\Delta t} & \big|\ t_0 < t_i \le \Delta t; 2\Delta t < t_i \le 3\Delta t; 4\Delta t < t_i \le 5\Delta t; \\ u_{i-1} & \big|\ \Delta t < t_i \le 2\Delta t; 3\Delta t < t_i \le 4\Delta t; 5\Delta t < t_i \le 6\Delta t; \\ u_{i-1} - \Delta u \dfrac{h_t}{\Delta t} & \big|\ 5\Delta t < t_i \le 6\Delta t; i = \overline{1, m_i}, \end{cases}$$

where Δt is subinterval duration;

$$m_i = (2t_0 + 8\Delta t)/h.$$

The program signal of six jacks is formed. Using registered sensor signals of jack linear movements $\{s_{дi},\ i = \overline{1,m_i}\}$, 6DOF position are calculated (see Figure 3 and Figure 4), average values of linear accelerations according to the *j*-th degree of freedom are calculated: $\ddot{s}_c = \frac{1}{n_c}\sum_{i=1}^{n_c} \ddot{s}_i$, where n_c is number of control steps in the subinterval, $n_c = \Delta t / h_t$. Calibration coefficients are determined.

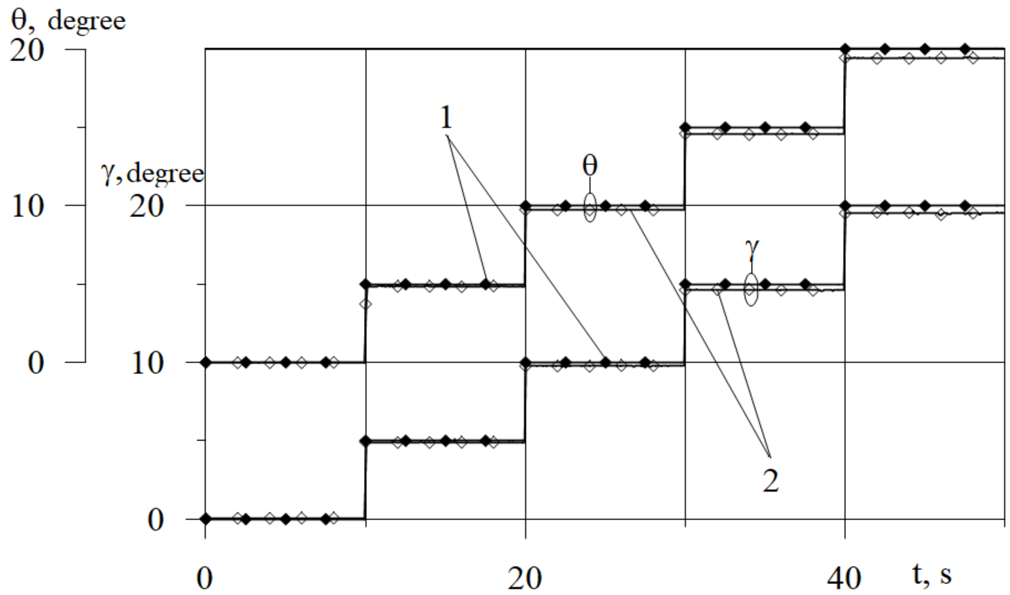

Figure 3 - Calculated (1) and registered (2) displacements of the 6DOF in terms of pitch and roll during sensor calibrations

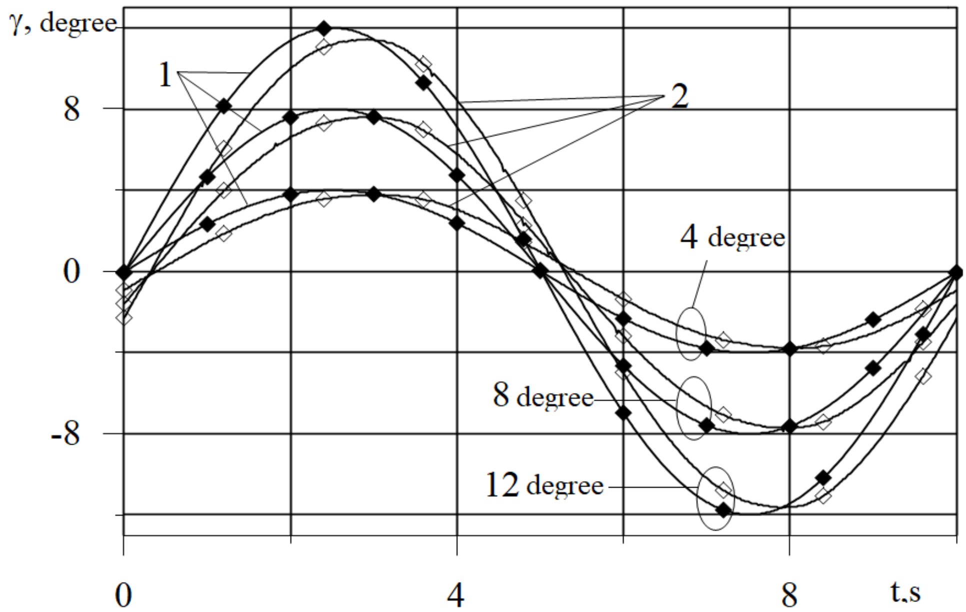

Figure 4 Calculated (1) and registered (2) displacements of the 6DOF in terms of roll during sensor calibrations

During 6DOF angular movements, signal amplitudes of angular acceleration sensors of roll, yaw, and pitch are respectively calculated by the formula: $\ddot{A}_p = A_u(2\pi f_u)^2$. To determine actual signal amplitudes of angular acceleration sensors, program signals are calculated according to corresponding degrees of freedom:

$$u_i = \begin{cases} 0 & \left| 0 \le t_i < t_0; t_0 + 4T_u \le t_i \le 2t_0 + 4T_u; \right. \\ A_u \sin(2\pi f_u t_i) & \left| t_0 \le t_i \le t_0 + 4T_u; i = \overline{1, m_i}, \right. \end{cases}$$

where $m_i = (2t_0 + 4T_u)/h_t$.

The jack program signals are formed, which, after 6DOF installation in the initial position, are fed to control unit inputs. The sensor signals of jack linear displacements $\{s_{дi}, i = \overline{1, m_u}\}$ and angular accelerations $\{\ddot{s}_{дi}, i = \overline{1, m_u}\}$ of the third period of 6DOF movement are registered (to avoid transient modes), the 6DOF positions are determined, which for roll movement are presented in figure 4. Angular acceleration sensor signals are decomposed into a Fourier series: $\ddot{s}_{дi} = a_0 + a_1 \cdot \cos(2\pi i/m_u) + b_1 \sin(2\pi i/m_u)$;, $i = \overline{1, m_u}$ where $m_u = T_u/h_t$, $a_0 = \frac{1}{m_u}\sum_{i=1}^{m_u} \ddot{s}_{дi}$, $a_1 = \frac{2}{m_u}\sum_{i=1}^{m_u} \ddot{s}_{дi} \cos\frac{2\pi i}{m_u}$, $b_1 = \frac{2}{m_u}\sum_{i=1}^{m_u} \ddot{s}_{дi} \sin\frac{2\pi i}{m_u}$ are Fourier coefficients. *i*-th series harmonic amplitude is determined by the formula: $A_1 = \sqrt{a_1^2 + b_1^2}$. The conversion factor is calculated: $k_a = A_1/\ddot{A}_p$.

Calibration of angular velocity sensors. 6DOF angular speed is calculated by the formula:

$$\dot{s}_i = \frac{\dot{s}_{дi} - \dot{s}_{дo}}{k_a}, \quad (5)$$

where $\dot{s}_{дi}$ is 6DOF angular velocity sensor signal at the i-th time;

$\dot{s}_{д0} = \frac{1}{n_0}\sum_{i=1}^{n_0} \dot{s}_{дi}$ is average value of angular speed sensor signals at a zero program signal

Calibration coefficients are determined by the formula obtained from (5): $k_a = (\dot{s}_{дi} - \dot{s}_{д0})/\dot{s}_i$. During 6DOF angular movement, sensor signal amplitudes of angular velocities along roll, yaw, and pitch are respectively calculated by the formula: $\dot{A}_p = 2\pi A_u f_u$. To determine actual signal amplitudes of angular velocity sensors, the program signal is calculated according to the corresponding degree of freedom:

$$u_i = \begin{cases} 0 & \left| 0 \le t_i \le t_0; t_0 + 4T_u \le t_i \le 2t_0 + 4T_u; \right. \\ A_u \sin(2\pi f_u t_i) & \left| t_0 \le t_i \le t_0 + 4T_u; i = \overline{1, m_i}; \right. \end{cases}$$

where $m_i = (2t_0 + 4T_u)/h_t$.

Jack program signals, which, after 6DOF installation in the initial position, are fed to control unit inputs. Sensors signals of jack linear displacements $\{s_{дi}, i = \overline{1, m_u}\}$ and angular velocities $\{\dot{s}_{дi}, i = \overline{1, m_u}\}$ of the third period of 6DOF movement are registered (to avoid transient modes), 6DOF position is determined. Angular velocity sensor signals are decomposed into the Four' series: $\dot{s}_{дi} = a_0 + a_1\cos(2\pi i/m_u) + b_1\sin(2\pi i/m_u); i = \overline{1, m_u}$, where $a_0 = \frac{1}{m_u}\sum_{i=1}^{m_u} \dot{s}_{дi}$, $a_1 = \frac{2}{m_u}\sum_{i=1}^{m_u} \dot{s}_{дi}\cos\frac{2\pi i}{m_u}$, $b_1 = \frac{2}{m_u}\sum_{i=1}^{m_u} \dot{s}_{дi}\sin\frac{2\pi i}{m_u}$; $m_u = T_u/h_t$. The amplitude of the i-th series harmonic is determined by the formula: $A_1 = \sqrt{a_1^2 + b_1^2}$. Calibration coefficient is calculated: $k_a = A_1/\ddot{A}_p$.

Conclusion.

Method of calibration of both linear and angular acceleration and angular velocity sensors was developed. Developed methodology of sensor calibration ensuring the possibility of determining of motion system characteristics and, upon request, adjusting them. Approbation of the methodology on the aircraft flight simulators Il-96-300, Tu-204 and An-74TK-200 showed its efficiency. So it may be used within system for determining of motion system characteristics.

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Анотація. *Характеристики динамічних стендів авіаційних тренажерів суттєво впливають на якість імітації акселераційних впливів і, таким чином, на відповідність тренажерів нормам придатності. Розроблено методику калібрування датчиків як лінійного, так і кутового прискорення та кутової швидкості. Розроблена методологія калібрування датчиків забезпечує можливість визначення характеристик динамічних стендів і, за потребою, їхнє корегування. Апробація методології на комплексних тренажерах літаків Іл-96-300, Ту-204 і Ан-74ТК-200 показала її ефективність.*

Ключові слова. *динамічний стенд авіаційного тренажера, калібрування датчиків.*