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OPTIMAL USE OF MOTION SYSTEM DESIGN RESOURCES FOR ANGULAR MOTION CUEING

Ua Запропоновано метод вирішення проблеми оптимального використання конструктивних ресурсів шестистепеневого динамічного стенду опорного типу авіаційного тренажера, що надає можливість поліпшення якості імітації кутових акселераційних дій. Оптимальне використання конструктивних ресурсів забезпечується використанням розробленого спрощеного оператора перетворення переміщень гідроциліндрів у переміщення динамічного стенду за окремими степенями вільності на засадах квадратичної апроксимації, розробленому критерій оцінки конструктивних ресурсів динамічного стенду за кутовими степенями вільності, сформульованій й розв'язаній задачі визначення залежностей координат осей тангажу й рискання від кута тангажу та залежності координат осей крену від кута крену. Завдяки оптимальному використанню конструктивних ресурсів динамічних стендів координати осі їхнього обертання за тангажем максимально можливо наближаються до координати осі літака. Таким чином, суттєво збільшується якість імітації акселераційних дій за кутовими степенями вільності.

En A method for solving the problem of optimal use of constructive resources of six degrees-of-freedom synergistic motion system of flight simulator is proposed, which provides an opportunity to improve the quality of angular motion cueing. Optimal use of constructive resources is ensured by using the developed simplified operator for transforming jack movements into motion system movements along individual degrees of freedom on the basis of quadratic approximation, the developed criterion for assessing constructive resources of motion system along angular degrees of freedom, the formulated and solved problem of determining the coordinate dependences both pitch and yaw axes coordinates from the pitch angle and the coordinate dependences of roll axes coordinates from the roll angle. Due to the optimal use of constructive resources of motion systems, the coordinates of the axis of their rotation along pitch are as close as possible to the coordinates of the aircraft axis. Thus, the quality of motion cueing along angular degrees of freedom is significantly increased.

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Introduction

Flight simulators have been applied principally to two applications: aircraft research and development and aircrew training. Motion cueing along angular degrees of freedom on flight simulators is of great importance, first of all, for pilot training. All the early pilot training devices from the Wright Brothers' simulator to Link's «blue box» tried to simulate airplane angular movements. Currently, motion cueing along angular degrees of freedom is a mandatory component of all full flight simulators [1]. The importance of motion cueing along angular degrees of freedom is due to the problem faced by the first pilots: the need to respond adequately to the atmospheric turbulence that caused aircraft angular movements.

Motion cueing along angular degrees of freedom is of great importance for maneuvering aircraft and modeling of critical flight modes (for example, stall mode and movements in a spin). The relevance of simulation of critical flight modes is confirmed by aircraft disasters that occurred recent years and were caused by inability of crew to recover aircraft from stall due to the lack of piloting skills in critical flight modes. One of the factors for insufficiently adequate simulation of aircraft critical flight modes on flight simulator is the lack of high-quality motion cueing along angular degrees of freedom. To solve this problem, the task of developing an effective motion cueing simultaneously along all angular degrees of freedom was set and solved. Thanks to its use, it is possible to significantly increase the operating ranges of motion system movements along angular degrees of freedom.

In Ukraine, there is a need to design flight simulators for designed aircraft and upgrading of existing flight simulators, which should meet modern requirements. So, problem of motion cueing along angular degrees of freedom is actual.

An interesting approach based on theoretical mechanics is proposed in the work [2]. However, it turned out to be ineffective. The calculations showed that for motion cueing along six degrees of freedom the 2-meter length jacks of motion system are insufficient.

An advanced design process applicable to motion cueing is presented in the paper [3]. This process is based on the analysis of the pilot-vehicle control loop by using a pilot model incorporating both visual and vestibular feedback, and the aircraft dynamics. After substituting the model for the simulated aircraft, the analysis tools are used to adjust the washout filter parameters with the goal of restoring pilot control behavior. The motion-base geometry is established based on practical limitations, as well as criteria for the stability of the platform with respect to singular conditions.

A set of experiments were conducted on the UTIAS flight research simulator [4] to determine the effects of translational and yaw motion on pilot performance, workload, fidelity, pilot compensation, and motion perception for helicopter yaw control tasks. The study found that yaw motion increased performance for the yaw capture and disturbance rejection tasks. Finally, the addition of yaw motion usually provided little benefit to performance, workload, compensation or fidelity, for all tasks.

The work [5] considers a wide range of issues related to training on flight simulators. Both the flight simulator itself and its systems, including motion cueing, are considered. The contribution of motion cueing to pilot training on simulators is given, as well as historical information and the main features of motion cue perception and simulation.

The paper [6] describes the process of designing an electromechanical actuator which can be used as a suitable replacement for jacks in simulation technology applications using six-degree-of-freedom motion platforms. The paper compares the operational and dynamic properties of hydraulic and electromechanical systems, proving that the latter can achieve better dynamics results. However, one has to take into consideration a decrease in the lifetime of the device as a consequence of increased wear and tear resulting from mechanical friction. Current trends and customer demand show that electromechanical motion platforms will gradually replace current hydraulic systems, the main reasons, apart from better dynamic properties, being significantly lower noise, increased ease of installation and better energy efficiency.

The results of research projects on pilot motion perception [7] have not only improved the knowledge on pilot's aircraft motion perception, but also initiated a reconsideration of motion feedback in flight simulation. Full flight simulation is meant to integrate the pilot's skill-based, rule-based and knowledge-based behavior in his control of the total aircraft system. Distinguishing the contribution of motion feedback to these three levels of behavior provides the tool to discriminate the impact of motion feedback on these levels of the resulting pilot behavior. The paper reviews the major results of the motion perception research and shows the impact on motion-base drive algorithm design.

The paper [8] presents state of the art motion cueing algorithms for a six degree of freedom driving simulator. Different types of algorithms are described and an appropriate choice is made taking in to account different criterions which are discussed subsequently. To ensure a proper implementation in the physical simulator of the algorithm selected, several simulations were carried out resulting in the simulator platform displacement.

The application of optimal control to simulator motion cueing is examined [9]. Existing motion cueing algorithms are hampered by the fact that they do not consider explicitly the optimal usage of simulator workspace. Numerical optimal control is used to minimize simulator platform acceleration errors, while explicitly recognizing the confines of the workspace.

The proposed method [10] ensures the optimal use of structural resources of flight simulator motion systems. On the basis of quadratic approximation, a simplified operator for converting jack movements into motion system movements along separate degrees of freedom was developed. The problem of determining both permissible movements and working movement ranges of motion system along linear degrees of freedom was formulated and solved. The criterion for evaluating motion system structural resources along linear degrees of freedom was developed. The problem of determining of dependence of both pitch and yaw axes coordinates from the pitch angle was formulated and solved.

The paper [11] analyzes the available mathematical models of flight simulator based on Stewart platform. The systems of equations obtained within framework of model connect both physical and geometric parameters of the Stewart platform; make it possible to determine reactions in upper hinges of platform mount, limiting values of angles of location in space of base of mount of the Stewart platform, under which condition of stable equilibrium operation of the Stewart platform is met.

A set of characteristic attributes of perception of motion cues is determined [12]. Based on the system approach principles, the mathematical formulation of the motion cueing problem along angular degrees of freedom on flight simulators of non-maneuvering aircraft is substantiated. This set-up guarantees motion cueing as close as possible to real ones based on the set of characteristic attributes of motion cue perception: character and direction fully correspond to the real ones, difference between perception time of motion cues on airplane and simulator is minimal and meets the current requirements, duration and intensity of motion cue perception on simulator are proportional duration and intensity of motion cue perception on airplane.

Problem statement

The purpose of this study is to determine ways to optimize the use of structural resources of six degrees-of-freedom synergistic motion system (DOF6) (Fig. 1) along angular degrees of freedom. This makes it possible to increase the efficiency of flight simulators for training pilots, it becomes possible to use DOF6 with jacks of a shorter length, and therefore to reduce the cost of their manufacture and operation.

Presentation of basic material

The object of this research is DOF6. All six jacks are involved in the movement of DOF6 along any degree of freedom (except roll movement, in which four jacks are involved). This leads to a strong interdependence of DOF6 movements along different degrees of freedom: movement along any degrees of freedom leads to a decrease in permissible movements along other degrees of freedom. The need to ensure the simultaneous movement of DOF6 along several degrees of freedom requires solving the problem of determining the movements of jacks depending on the necessary movements of DOF6 along degrees of freedom.

The transformation matrix from the connected coordinate system *OXYZ* to the Earth coordinate system $O_gX_gY_gZ_g$ [13] A_{tm} is:

$$A_{tm} = \begin{pmatrix} \cos\psi\cos\theta & \sin\theta & -\cos\theta\sin\psi \\ -\sin\theta\cos\psi\cos\gamma+\sin\psi\sin\gamma & \cos\theta\cos\gamma & \cos\psi\sin\gamma+\sin\theta\sin\psi\cos\gamma \\ \sin\theta\cos\psi\sin\gamma+\sin\psi\cos\gamma & -\cos\theta\sin\gamma & \cos\psi\cos\gamma-\sin\theta\sin\psi\sin\gamma \end{pmatrix} \quad (1)$$

Quadratic approximation implies replacing the trigonometric functions of angles with angles themselves and preserving in (1) the values of only the first and second order of smallness. Considering the angles to be small and taking into account the small range of their change, in the scalar form the coordinates of rotation centers of jack upper hinges in the Earth coordinate system $O_gX_gY_gZ_g$ (1) are described by the equations:

$$x_{vk} = x + x_{vk}\left[1-0{,}5\left(\psi^2+\theta^2\right)\right] + z_{vk}\left(\theta+\psi\right);$$
$$y_{vk} = y + x_{vk}\theta - z_{vk}\gamma + Y_{vp}; \quad (2)$$
$$z_{vk} = z - x_{vok}\psi + z_{vok}\left[1-0{,}5\left(\psi^2+\gamma^2\right)\right], \quad k=\overline{1,6},$$

where Y_{vp} is the coordinate of rotation centers of jack upper hinges along the vertical axis *OY* in the initial position of DOF6, x_{nk}, z_{nk} are the coordinates of the rotation centers of the k–th jack lower hinges in the Earth coordinate system $O_gX_gY_gZ_g$ along the O_gX_g and O_gZ_g axes;

l_{vp} is the average length of the jacks, which corresponds to the initial position of DOF6 and is equal to half the working stroke of jack rods $l_{vp} = \left(l_{max} - l_{min}\right)/2$. In the last equation, l_{max}, l_{min} are, respectively, the length of jack rods with the rod maximally extended and maximally retracted. These lengths are defined as the distances between the upper and lower rotation centers of the jack hinges along the direction of jack when rod is fully extended and fully retracted.

By approaching the roll axis closer to the jack that may become critical first (a jack whose rod is in the extreme extended or retracted position is called critical), it is possible to increase the working ranges of motion system movements along angular degrees of freedom. In addition, there is a possibility, depending on the specific needs of motion cueing, to increase to one degree or another the working range of motion system movements along a given angular degree of freedom. Thus, one of the most important tasks is to expand the operating ranges of motion system movements along the roll and pitch while ensuring the minimum required range of motion system movements along the yaw.

To achieve this goal, the coordinates of the roll and yaw axes were described by cubic spline functions [14].

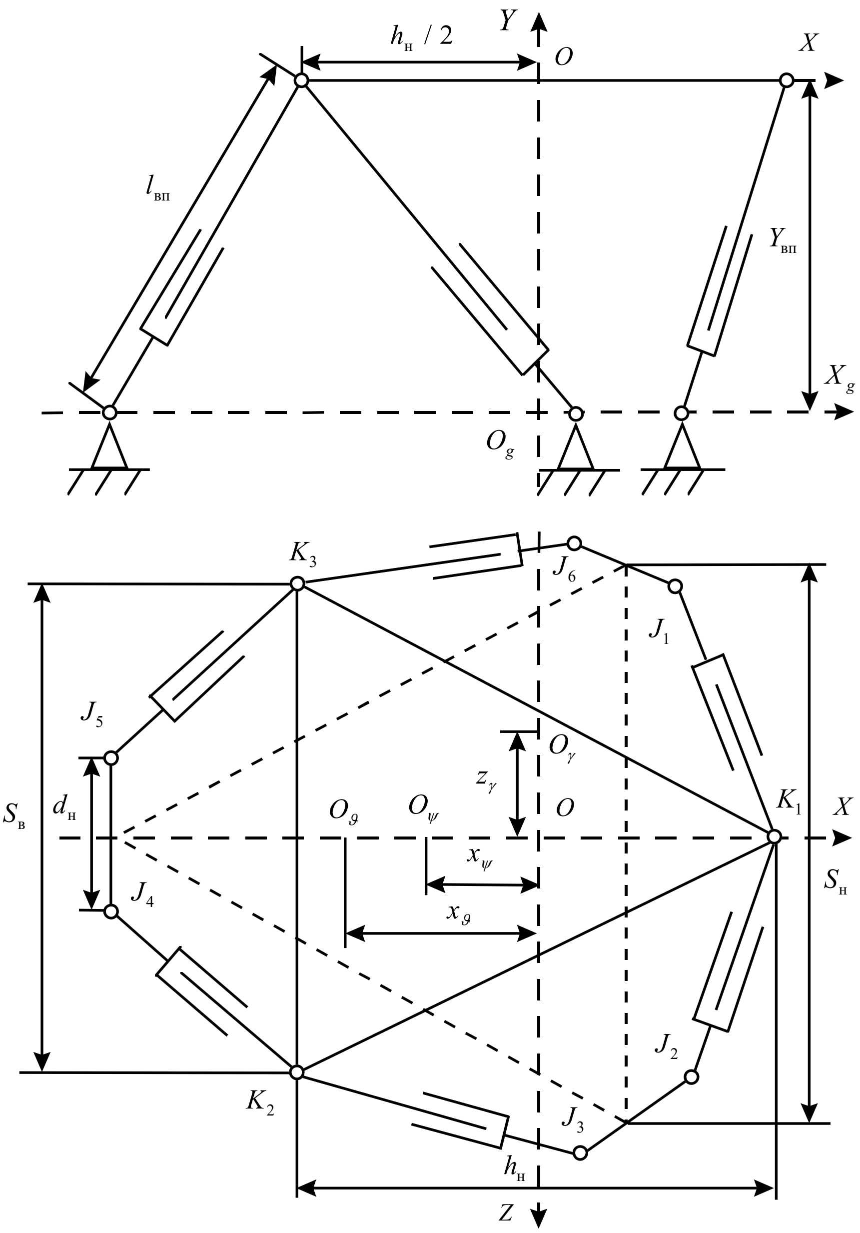

Fig. 1. Kinematic scheme of DOF6

$$x_\psi(\vartheta)=\begin{cases} x_\psi^- \Big| \vartheta \le \vartheta_{\psi 1} = -\vartheta^*; \\ \left[\begin{matrix} M_{\psi i}\left(\vartheta_{\vartheta(i+1)}-\vartheta\right)^3 + M_{\vartheta(i+1)}\left(\vartheta-\vartheta_{\vartheta i}\right)^3 + \\ \left(6x_{\vartheta i} - M_{\vartheta i}h_{\vartheta i}^2\right)\left(\vartheta_{\vartheta(i+1)}-\vartheta\right)+ \\ +\left(6x_{\vartheta(i+1)} - M_{\vartheta(i+1)}h_{\vartheta i}^2\right)\left(\vartheta-\vartheta_{\vartheta i}\right) \end{matrix}\right] \Big/ 6h_{\vartheta i}\vartheta_{\vartheta i} < \vartheta \le \vartheta_{\vartheta(i+1)} \\ x_\vartheta^+ \Big| \vartheta > \vartheta_{\vartheta n\vartheta} = \vartheta^*; \end{cases} \quad (3)$$

$$z_\gamma(\gamma)=\begin{cases} \mathrm{sign}(\gamma\vartheta)\, z_{\bar{\gamma}} \,\big|\, \gamma \le \gamma_{\gamma 1} = \gamma^*; \\ sign(\gamma\vartheta)\Big[M_{\gamma i}\left(\gamma_{\gamma(i+1)}-\gamma\right)^3 + M_{\gamma i}\left(\gamma-\gamma_{\gamma i}\right)^3 + \\ +\left(6z_{\gamma i}-M_{\gamma i}h_{\gamma i}^2\right)\left(\gamma_{\gamma(i+1)}-\gamma\right)+ \\ +\left(6z_{\gamma(i+1)}-M_{\gamma(i+1)}h_{\gamma i}^2\right)\left(\gamma-\gamma_{\gamma i}\right)\Big]/6h_{\gamma i} \quad \Big| \gamma_{\gamma i} < \gamma \le \gamma_{\gamma(i+1)},\ i=\overline{1,n_\gamma-1}; \\ x_\vartheta^+ \,\big|\, \vartheta > \vartheta_{\vartheta n \vartheta} = \vartheta^*; \end{cases}$$

where $\theta_{\psi i}$ is the *i*-th point of division of the working pitch range of DOF6 into subintervals $\left[\theta_{\psi i};\theta_{\psi(i+1)}\right], i=\overline{1,n_\psi-1};$

i is the index of the dividing point of the working pitch range of DOF6;

n_ψ is the number of points of division of the working pitch range of DOF6 into subintervals $\left[\theta_{\psi i};\theta_{\psi(i+1)}\right], i=\overline{1,n_\psi-1};$

$x_{\psi i}$ is the coordinates of the yaw axis of DOF6 along the longitudinal axis *OX* at the *i*-th point of division of the working range of DOF6 pitch into subintervals $\left[\gamma_{\gamma i};\gamma_{\gamma(i+1)}\right], i=\overline{1,n_\gamma-1};$

z_γ^-, z_γ^+ are respectively, the coordinates of motion system roll axis along the longitudinal axis *OZ*, corresponding to the limiting negative $-\gamma^*$ and positive $+\gamma^*$ values of motion system roll operating range;

$z_{\gamma i}$ is the coordinate of the roll axis along the longitudinal axis OZ at the i-th point of division of motion system roll operating range $[-\gamma^*; +\gamma^*]$ into subintervals $\left[\gamma_{\gamma i};\gamma_{\gamma(i+1)}\right], i=\overline{1,n_\gamma-1};$

n_γ is the number of points of division of motion system roll operating range $[-\gamma^*; +\gamma^*]$ into subintervals $\left[\gamma_{\gamma i};\gamma_{\gamma(i+1)}\right], i=\overline{1,n_\gamma-1};$

$\gamma_{\gamma i}$ is the i-th point of division of motion system roll operating range $[-\gamma^*; +\gamma^*]$ into subintervals $\left[\gamma_{\gamma i};\gamma_{\gamma(i+1)}\right], i=\overline{1,n_\gamma-1};$

$h_{\gamma i}=\gamma_{\gamma(i+1)}-\gamma_{\gamma i}$ are steps of division;

$M_{\psi i}=\ddot{x}_\psi\left(\theta_{\psi i}\right),\ M_{\gamma i}=\ddot{z}_\gamma\left(\theta_{\psi i}\right)$ are constant coefficients;

$h_{\psi i}=\theta_{\psi(i+1)}-\theta_{\psi i}$ is partition steps.

The values of the pitch and yaw axes along the longitudinal axis *OX* at the points of division of DOF6 operating range $\{z_\gamma\}$ and $\{x_\psi\}$ and the constant coefficients of the cubic spline functions $\{M_\gamma\}$ and $\{M_\psi\}$ were found.

The geometric meaning of the problem of determining the working ranges of motion system movements along angular degrees of freedom is reduced to fitting into the region of possible motion system positions $\tilde{U}$ a parallelepiped

$\tilde{P}_{\gamma\psi\vartheta}$, the length of one edge of which is equal to the minimum required range of motion system movements along yaw, and the lengths of the other two edges are not less than the minimum required ranges of motion system movements along roll and pitch

$$\tilde{P}_{\gamma\psi\vartheta} = \left\{ (x,\psi,\vartheta) \middle| \gamma^* \geq \gamma_{\min}, -\psi_{\min} \leq \psi \leq \psi_{\min}, \vartheta^* \geq \vartheta_{\min} \right\}.$$

The cubic spline functions of the dependences of the coordinates of the yaw axes along the pitch angle, the cubic spline function of the dependence of the roll axis coordinate along the roll angle, the working ranges of motion system movements along roll and pitch were searched. The sum of the working ranges of motion system movements along these degrees of freedom should be maximal

$$\gamma^* + \vartheta^* \to \max, \ \tilde{P}_{\gamma\psi\vartheta} \subset \tilde{U} ..$$

The basis for assessing the use of structural resources of motion system along angular degrees of freedom is the dependence of the permissible displacements of motion system along the pitch angle $\bar{\gamma}(\vartheta)$:

$$\bar{\gamma}(\vartheta) \to L^{\max}_{ja,\psi,\vartheta}; \quad \left(L_{ja} \in \Omega_l; \ -\vartheta^* \leq \vartheta \leq \vartheta^*; \ -\psi^* \leq \psi \leq \psi^* \right).$$

The unused structural resource of motion system along angular degrees of freedom is determined by the discrepancy between the permissible displacement of motion system and the working range of displacement along roll. Ideally, the structural resource of motion system should be used in full and the permissible displacement of motion system along roll should be equal to the working range of motion system displacement. To assess the use of structural resources of motion system along angular degrees of freedom, it is necessary to use the criterion

$$J_\gamma = \int_{-\vartheta^*}^{\vartheta^*} \left| \bar{\gamma}(\vartheta) - \gamma^* \right|^2 d\vartheta.$$

The problem of effective use of structural resources of motion system is reduced to an extreme problem:

$$J_\gamma \to L^{max}_{ja,\bar{\gamma},\psi,\vartheta}; \quad \begin{pmatrix} L_{ja} \in \Omega_l; \bar{\gamma}(\vartheta) - \gamma^*; -\dfrac{h}{2} \leq z_\gamma \leq \dfrac{h}{2}; \\ -\vartheta^* \leq \vartheta \leq \vartheta^*; -\gamma^* \leq \gamma \leq \gamma^*; -\psi^* \leq \psi \leq \psi^* \end{pmatrix}. \qquad (4)$$

Research results

The results of calculations (4) show (fig. 2) significant advantages of maximum use of the structural resource DOF6. Thus, with the traditional approach, the operating ranges of motion system movements along yaw $\psi^* = 4$ degrees, along pitch $\vartheta^* = 12$ degrees and along roll $\gamma^* = 10{,}4$ degrees, and with the maximum use of the structural resources of DOF6, the operating ranges of motion system movements along yaw $\psi^* = 4$ degrees, along pitch $\vartheta^* = 12$ degrees and along roll $\gamma^* = 19.2$ degrees. That is, the operating range of motion system movements along roll has almost doubled. The calculated dependencies of the roll axis coordinate from the roll angle and the yaw and pitch axis coordinates from the pitch angle (a modified deformable polyhedron method was used) are shown in fig. 3.

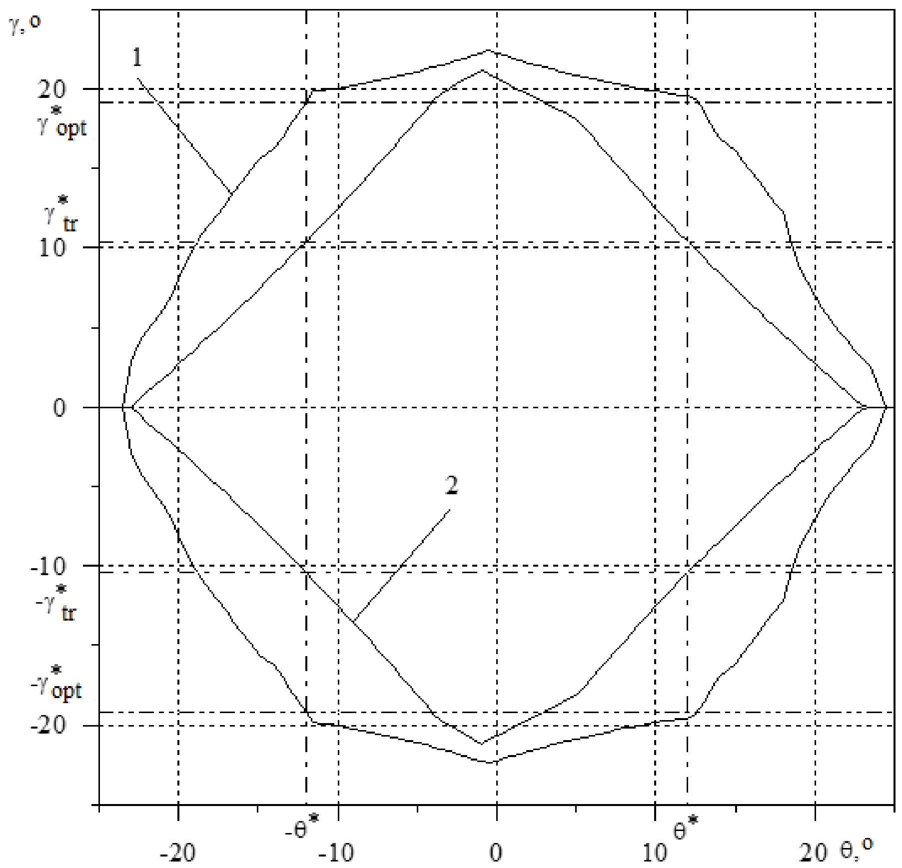

Fig. 2. Permissible roll movements with the developed (1) and traditional approach (2)

Conclusion

Proposed method for solving the problem of optimal use of constructive resources of six degrees-of-freedom synergistic motion system of flight simulator improves the quality of angular motion cueing. This was achieved thanks to developed simplified operator for transforming jack movements into motion system movements along individual degrees of freedom on the basis of quadratic approximation, the developed criterion for assessing constructive resources of motion system along angular degrees of freedom, the formulated and solved problem of determining the coordinate dependences both pitch and yaw axes coordinates from the pitch angle and the coordinate dependences of roll axes coordinates from the roll angle, the optimal use of constructive resources of motion systems, the coordinates of the axis of their rotation along pitch are as close as possible to the coordinates of the aircraft axis. Thus, the quality of motion cueing along angular degrees of freedom is significantly increased.

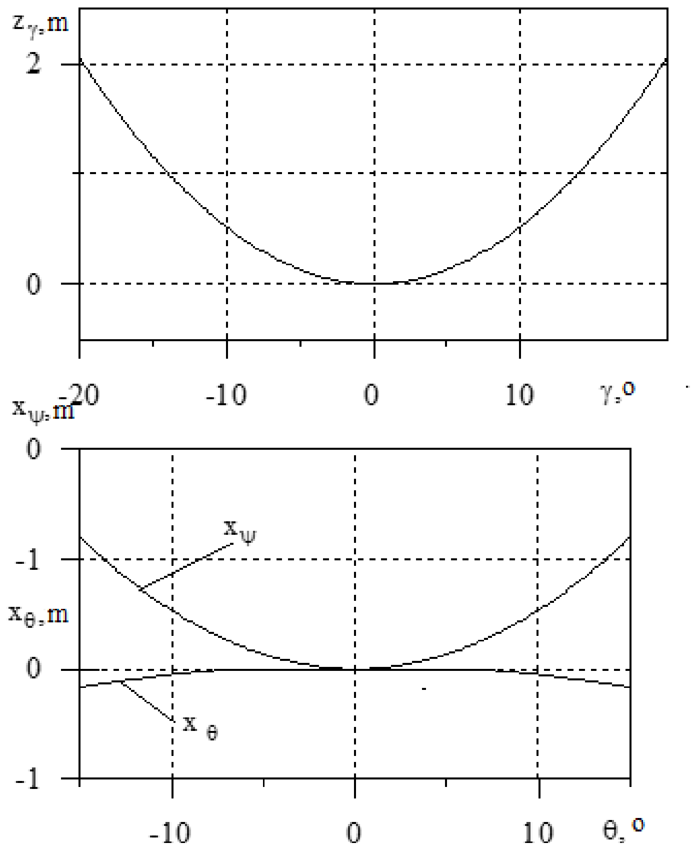

Fig. 3. Calculated dependencies of the roll axis coordinates from the roll and yaw and pitch axes from the pitch

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