УДК 629.736.072.8; 681.3
DOI: https://doi.org/10.20535/0203-3771422021268892

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PROBLEM OF MOTION CUEING ALONG LINEAR DEGREES OF FREEDOM ON FLIGHT SIMULATORS

Ua На засадах теорії сприйняття Гібсона визначена сукупність характеристичних ознак сприйняття людиною акселераційних діянь. На засадах системного підходу обґрунтована математична постановка задачі імітації акселераційних діянь за лінійними степенями вільності на авіаційних тренажерах неманеврових літаків. Така постановка гарантує імітацію акселераційних діянь максимально наближених до реальних за сукупністю характеристичних ознак сприйняття акселераційних діянь: характером, початковим часом, напрямком, тривалістю та інтенсивністю сприйняття.

En On the basis of Gibson's perception theory, a set of characteristic attributes of human motion perception is determined. On the basis of the system approach, the mathematical statement of the motion cueing problem along linear degrees of freedom on flight simulators of non-maneuvering aircraft is substantiated. This statement guarantees a motion cueing as close as possible to the real set of characteristic attributes of the motion cueing: nature, beginning time, direction, duration, and intensity of perception.

Statement of problem

A flight simulator is the most important technical device for pilot training. Flight simulators have come a long way: from primitive devices to Link's “blue box” and to motion systems that fully simulate the entire process of pilot activity

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on the ground. Flight simulators consist of several interconnected and interacting systems, one of the most important from them is a motion system that provides pilots with motion cues.

A motion cue is a physical action. The motion cue can be perceived by the human's vestibular system according to aircraft position and motion in space. The motion cue is a source of information that cannot be ignored and that both constantly and actively maintains the pilot's awareness of the condition, position, and nature of aircraft movement. So, the motion cues are crucial for the formation of piloting skills, improving pilot efficiency, and reducing mental stress and workload. Flight simulator efficiency and transfer of piloting skills from a flight simulator to aircraft depend on motion cueing fidelity.

The study of motion cueing influence on pilot training effectiveness on flight simulators [1] shows both an increase in control column deviations (Fig. 1) and piloting difficulty on flight simulator without a motion system. Delay of pilot's reaction in absence of motion system (0,7 s) is significantly greater than in presence of a motion system (0,4 s).

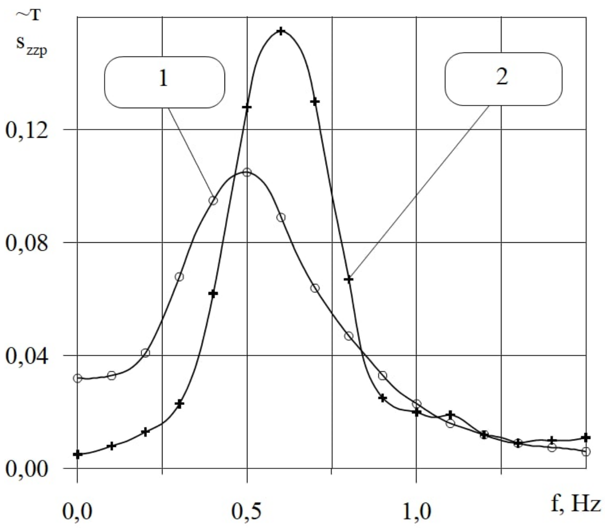

Fig. 1. Spectral density of control column deviations [1]:
1 – without motion system; 2 – with the motion system

For motion cueing a flight simulator compartment is mounted on a mobile basis—motion system. The movement of the motion system creates motion cues. First motion systems appeared in the forties. Now, in accordance with current requirements, the motion system is an essential component of high-quality flight simulators. The flight simulators are designed and manufactured by such large enterprises as CAE Electronics (Canada), Thales Training & Simulation (France), and Penza' Modeling Design Bureau (Russia), and, on the other hand, by such aviation enterprises such as State Enterprise "Antonov".

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, the problem of motion cueing along linear degrees of freedom is actual.

Analysis of last achievements and publications

Many investigations [1 - 11] of motion cueing were conducted in order to increase motion cueing fidelity. Motion cueing as in real flight is possible only with accurate reproduction of aircraft spatial motion. Due to limited constructive resources of flight simulator in comparison with aircraft resources, it is impossible to continuously monitor an aircraft's movement. On the other hand, only motion perception is important for the pilot. Therefore, during motion cueing, the movement of the motion system itself is not so important, but the created motion cues and how much their perception on the flight simulator corresponds to real ones with the same control actions.

The vestibular apparatus has a number of features that significantly effect motion cue perception. First, an important parameter of the vestibular analyzer's functional state is the latent period (latency time) – a time delay between a motion cue beginning and a motion sensation appearance. Second, due to the presence of specific formations in vestibular system receptors that functioning as threshold devices, there is a threshold of vestibular analyzer sensitivity receptors. It is the minimum value of the motion cue, which causes a noticeable motion sensation. In other words, below this threshold, a person does not feel motion. Third, the human vestibular apparatus is characterized by adaptation to motion cues. Due to adaptation, perceived motion parameters may differ from the actual ones. Fourth, the vestibular response can be changed significantly with a person's mental state.

The best mathematical model of otoliths that perceive motion cues along linear degrees of freedom is the Meiry's model in the form of a linear operator and a series-connected nonlinear element of insensitivity zone type, which describes the perception threshold:

$$\ddot{\Omega} = a_0 \dddot{s} - a_1 \dot{\Omega} - a_2 \Omega, \quad \Omega_n,$$

where $\ddot{\Omega}$, $\dot{\Omega}$ is motion perception function, its first and second derivatives;

Ω is a function of linear motion perception (indication of motion cue perception is exceeding of perception threshold with motion perception function);

Ω_n is motion perception threshold;

a_0, a_1, a_2 is perception mathematical model coefficients;

$\dddot{s}$ is the third derivative of displacement.

The research was conducted both on a flight simulator and on non-maneuverable aircraft in real flight. Appropriate models of motion perception along linear degrees of freedom were constructed

$$\Omega_x = \dddot{s}_x - 1{,}64 \cdot s_x - 0{,}21\Omega_x\,, \quad \Omega_{nx} = 0{,}23^{+0{,}10}_{-0{,}09}\,;$$

$$\Omega_y = \dddot{s}_y - 1{,}64 \cdot s_y - 0{,}25\Omega_y\,, \quad \Omega_{ny} = 0{,}626^{+0{,}17}_{-0{,}17}\,;$$

$$\Omega_z = \dddot{s}_z - 1{,}64 \cdot s_z - 0{,}20\Omega_z\,, \quad \Omega_{nz} = 0{,}169^{+0{,}20}_{-0{,}041}\,,$$

where x, y and z are the longitudinal, vertical, and lateral degree of freedom respectively.

These models are acting as nonlinear filters and reflect the peculiarities of human motion perception and dynamic properties of the human vestibular system, quantify a motion sensation depending on kinematic parameters of aircraft motion, and are suitable for effective use in motion cueing. Due to some essence of human motion perception regardless of the linear degree of freedom, they have identical structures and represent a differential equation of the second order, the input of which receives kinematic motion parameters, and the output of which allows for assessment a motion perception by a pilot.

Formulation of purpose

Due to the high cost of a motion system and growing requirements for motion cues fidelity, it is necessary to develop an effective method of motion cueing along linear degrees of freedom on non-maneuvering aircraft. Perception of force cueing should be as close as possible to the perception of real force cues.

Presentation of basic material

The determination problem of maximum motion cue occurrence frequency along the vertical degree of freedom was solved for the identification of motion cue occurrence peculiarities. The mathematical model of non-maneuverable aircraft was used in calculations. The control signal calculations were based on rudder driving actuator characteristics: sinusoidal control law was significantly distorted, and impulse law straight front was transformed into an inclined one, the angle of which was determined by energy drive capabilities. The deflection speed of the control column was accepted as maximum. The deflection amplitude was limited with the control column excursion, the ability to maintain the control law shape for a given control frequency, and the allowable overload. To create limit flight modes, it was assumed that pilot did not have regulated piloting techniques.

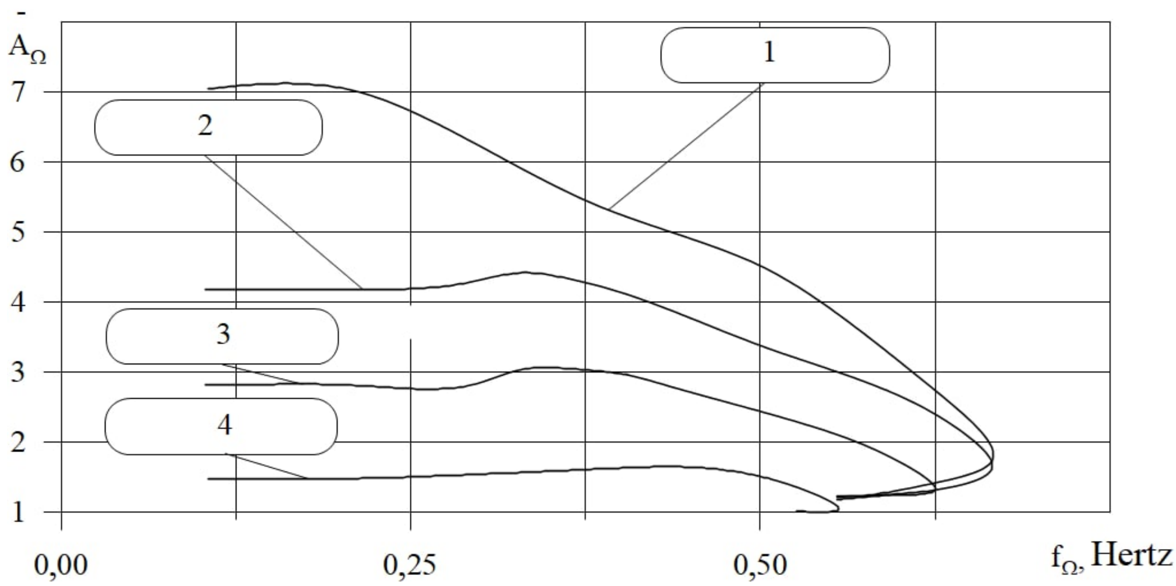

Fig. 2. Dependence of relative amplitude of motion perception function on motion cue frequency along the vertical degree of freedom: 1 – x_{cc} = 0,1 m; 2 – x_{cc} = 0,06 m; 3 – x_{cc} = 0,04 m; 4 – x_{cc} = 0,02 m

Fig. 2 shows the relative amplitudes of motion perception function $\left(\bar{A}_\Omega = \Omega/\Omega_n\right)$ of the system "aircraft-ideal pilot" along the vertical degree of free dom. (The condition for a motion cue perception is the achievement of the unit with relative amplitude of motion perception function: $\bar{A}_\Omega \geq 1$).

Calculated vertical acceleration, motion perception functions, and control column deflections are shown in Fig. 3. As can be seen from this figure, the maximum frequency of perceived motion cue along the vertical degree of freedom is 0,7 Hz. Thus, the minimum time interval between the appearances of perceived motion cues along vertical degree of freedom is 1,4 s. In addition, it was found that at a change of the control wheel deflection from 0,065 m to 0,08 m, the maximum frequency of motion cue along the vertical degree of freedom increases to 0,72 Hz. As the degree of stability decreases, the dependence of the relative amplitude of motion perception function on motion cue frequency along the vertical degree of freedom changes: there is the maximum frequency of motion cue along the vertical degree of freedom. The decrease of motion cue frequency along the vertical degree of freedom is due to the fact that the inverted acceleration signal has a smaller amplitude and motion is not perceived.

According to Gibson's perception theory, a human perceives information with characteristic attributes. Characteristic attributes of motion cues are nature, beginning time, direction, intensity, and duration of perception.

There are dynamic (over 0,3 Hz) and static (up to 0,3 Hz) motion cues along the linear degrees of freedom, namely:

– dynamic motion cues along the longitudinal, vertical, and lateral degrees of freedom;
– static motion cues along the longitudinal degree of freedom.

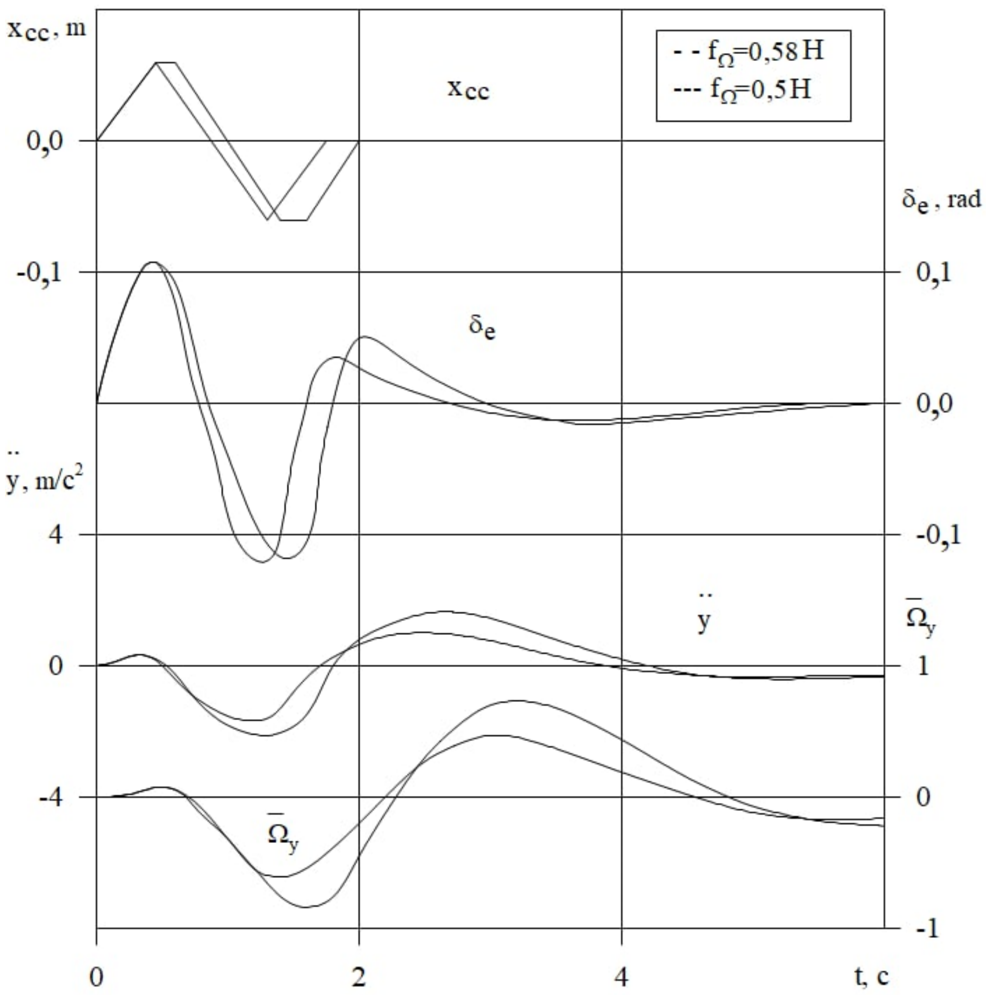

Fig. 3. Reaction of non-maneuverable aircraft model along the vertical degree of freedom at different rudder deviations

Conditions that serve as the basis for high-quality motion cueing may be formulated on the peculiarities of human motion perception:
– characteristics attributes of perceived motion cues: a beginning time, a direction, an intensity and a duration of perception should be simulated;
– nature of motion perception on flight simulator should be such as real (during motion cueing should be absent false motion cues);
– the difference between a beginning time of motion perception on aircraft and a flight simulator should be minimum and be within the requirements;
– direction of motion perception on flight simulator should correspond to real;
– intensity and duration of motion cues should be proportional to the intensity and duration of motion cues occurring in actual flight.

Due to the finite speed of processes on flight simulators, motion cues have some time delays, which can worsen the pilot's activity on a flight simulator.

Due to limited constructive resources of flight simulator in comparison with aircraft resources, it is impossible to continuously monitor an aircraft motion perception function Ω_a and the motion perception function on a flight simulator Ω_{fs} has gaps and differs from an aircraft motion perception function Ω_a (Fig. 4). To ensure a coincidence of a perception beginning time on a flight simulator and aircraft, an aircraft forecast motion perception function is calculated (predictive values of aircraft motion perception function at the time $t+\Delta\tau$):

$$\bar{\Omega}_{aj} = \Omega_{aj} + \Delta\tau_j \dot{\Omega}_{aj} + 0,5\Delta\tau_j^2 \ddot{\Omega}_{aj}, \quad j = \overline{1,3}.$$

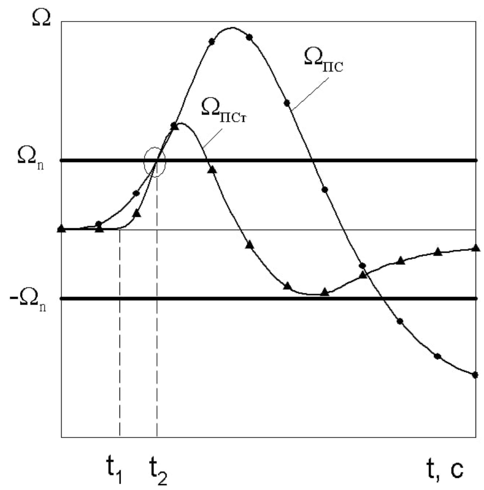

Fig. 4. Perception of motion cues on aircraft and flight simulator

An aircraft motion perception function Ω_a begins to differ from zero at time $t=0$. At time t_1, a forecast motion perception function of aircraft $\bar{\Omega}_a$ reaches a threshold Ω_n value and motion cueing start on flight simulator. To coincide the times of motion perception beginning on aircraft and flight simulator (time t_2) the starting movement of flight simulator should be more intense than the aircraft movement, and the value of forecast time of aircraft motion perception function (with control signals of different intensity, creating motion cues in a range from the minimum that almost little different from perception threshold, to the maximum that can be created on this flight simulator) for a particular flight simulator and a specific aircraft (i. e., taking into account the dynamic characteristics of flight simulator and aircraft) for each degree of freedom $\Delta\tau = \left[\Delta\tau_x, \Delta\tau_y, \Delta\tau_z\right]^{\mathrm{T}}$ is selected so that difference between motion perception on aircraft and flight simulator should be minimal and within current requirements.

Vector of derived predictive aircraft motion perception function $\dot{\bar{\Omega}}_a = \left[\dot{\bar{\Omega}}_{ax}, \dot{\bar{\Omega}}_{ay}, \dot{\bar{\Omega}}_{az}\right]^{\mathrm{T}}$ is calculated for determination of perceived motion intensity:

$$\dot{\bar{\Omega}}_{aj} = \dot{\Omega}_{aj} + \Delta\tau_j \dot{\Omega}_{aj}, \quad j = \overline{1,3}.$$

Methodologically, the motion cueing on flight simulator is a very complex problem, which can be solved only with the careful agreement of information about the movement of aircraft and flight simulator. Due to the presence of the system factor – the quality of motion cueing (which means the degree of approximation of motion perception on flight simulator and aircraft) – the problem of motion cueing should be formulated on basis of a systematic approach.

Signs of the motion perception function of aircraft Q_a and flight simulator Q_{fx} should coincide if modules of the motion perception function of aircraft Q_a and flight simulator Q_{fx} are higher than the perception threshold Q_a, and module of predictive motion perception function of aircraft $|\bar{\Omega}_a|$ has reached or exceeded the perception threshold Q_n and if modules of motion perception function of aircraft $|\bar{\Omega}_a|$ and flight simulator $|\bar{\Omega}_{fs}|$ are greater than the perception threshold Q_n, and may not coincide when motion perception function of aircraft Q_a is higher than the perception threshold Q_n, and module of motion perception function of flight simulator Q_{fx} lower than the perception threshold Q_n

$$\mathrm{sign}\Omega_{fs} = \begin{cases} \mathrm{sign}\Omega_a \left| \begin{array}{c} |\bar{\Omega}_a| \geq \Omega_n, \ |\Omega_a| < \Omega_n, \ |\Omega_{fx}| < \Omega_n; \\ |\Omega_a| \geq \Omega_n, \ |\Omega_{fx}| \geq \Omega_n; \end{array} \right. \\ \pm\mathrm{sign}\Omega_a \left| |\bar{\Omega}_a| \geq \Omega_n, \ |\Omega_a| \geq \Omega_n, \ |\Omega_{fx}| < \Omega_n, \right. \end{cases}$$

where $\Omega_{fs} = \left[\Omega_{fsx}, \ \Omega_{fsy}, \ \Omega_{fsz}\right]^{\mathrm{T}}$ is a vector of motion perception function of the flight simulator.

As an assessment criterion of perceived motion cues, it is natural to use the functionality $J = \left[J_x, \ J_y, \ J_z, \ J_\gamma, J_\psi\right]^{\mathrm{T}}$ that evaluates the error of coincidence of motion cueing perception on aircraft and flight simulator:

$$J = \int_0^{\mathrm{T}} \left|\Omega_a(t) - \Omega_{fs}\left[u(t)\right]\right| dt| \ |\Omega_a(t)| > \Omega_n, \tag{1}$$

where $u = \left[u_x, u_y, u_z\right]^{\mathrm{T}}$ is the vector of the program signal, and reduce the problem of motion cueing to the synthesis of program signal that minimizes the functionality (1):

$$J(u) = \min \Rightarrow u(t) \quad \dot{\Omega}_{fs} \to \dot{\Omega}_a$$

$$\mathrm{sign}\dot{\Omega}_{fs} = \mathrm{sign}\dot{\Omega}_{a} \qquad \left|t_{fs} - t_{a}\right| = \min < t_{r} ,$$

where t_{α}, t_{fs} is the beginning time of motion perception on aircraft and flight simulator respectively,

t_{r} is requirement difference between beginning time of motion perception on aircraft t_{α} and flight simulator t_{fs}.

Conclusion

The proposed formulation of the problem of motion cueing along linear degrees of freedom shows the main directions of increasing of motion cue fidelity and, first of all, the development of an effective methodology for motion cueing along linear degrees of freedom.

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