UDC 629.736.072.8; 681.3
DOI: https://doi.org/10.20535/0203-3771432022275343

V. V. Kabanyachyi[1], *Dc.of Science*, **S. V. Hrytsan[2]**, *PhD student*

MOTION CUEING ALONG SEPARATE DEGREES OF FREEDOM ON FULL FLIGHT SIMULATORS

Ua Система рухомості одна з найважливіших складових тренажерів. Для високої якості імітації акселераційних впливів була розроблена методика імітації акселераційних впливів за окремими степенями вільності. На засадах результатів досліджень на комплексному тренажері літака Ан-74ТК-200 розроблена методика враховує сприйняття пілотом руху за фізичним та диференційним порогами. Апробація методики на тренажерах транспортних літаків показала її високу ефективність.

En Motion system is one of the most important components of flight simulators. For high quality of motion cueing method of motion cueing along separate degrees of freedom was developed. Based on the research results on the An-74TK-200 full flight simulator, method takes into account the pilot's movement perception with both physical and differential thresholds. Approbation of the methodology on transport aircraft simulators has showed its high efficiency.

Statement of problem

A flight simulator is a device that artificially re-creates an aircraft flight and the environment in which it flies. It is used for a variety of reasons, including flight training, design and development of aircraft itself, and research into aircraft characteristics and control handling qualities. A full flight simulator (Fig. 1) means a full size replica of a specific type or make, model and series aircraft cockpit. It is composed from several interconnected and interacting systems (flight dynamics, visual, motion, sound etc.) that form a system with closed control circuit. Flight simulation may be defined as creating, in real time under non-flight conditions of a specific aircraft including its environment with required fidelity as on an actual aircraft. Due to necessity of big constructive resource for motion cueing along separate degrees of freedom it is one of important component of motion cueing.

In the world a flight simulator design and manufacture is carried out with such large companies as CAE Electronics (Canada), Thales Training & Simulation (France) and, on the other hand, with separate aviation enterprises, in particular Antonov State Enterprise. In Ukraine, there is a need to design full flight simulators for designing aircraft and modernization of existing full flight simula-

[1] *Igor Sikorsky Kyiv polytechnic institute*
[2] *Igor Sikorsky Kyiv polytechnic institute*

tors. Therefore, motion cueing along separate degrees of freedom is actual problem for Ukraine.

Fig. 1. Modern full flight simulator

Analysis of last achievements and publications

Motion cue is a physical action caused by position and motion of aircraft and which can be perceived with human vestibular system. For motion cueing a full flight simulator cockpit is mounted upon motion platform. Motion platform must motion cueing along all six degrees of freedom that can be experienced with body that is free to move in space. Many investigations were conducted for improvement of motion cueing [2 – 13].

Young' model is the best perception model of motion cues along angular degrees of freedom. This model form is both linear operator and consistently connected nonlinear element of insensitivity zone type describing a perception threshold:

$$\ddot{\Omega} = a_0\ddot{s} - a_1\dot{\Omega} - a_2\Omega\,,\ \ \Omega_t\,, \qquad (1)$$

where Ω is motion perception function;

Ω_t is motion perception threshold;

a_0, a_1, a_2 are coefficients of motion perception model;

$\ddot{s}$ is an angular acceleration.

Meyri' model is the best mathematical model of motion cues along linear degrees of freedom. This model form is both linear operator and sequentially connected nonlinear element of insensitivity zone type describing a perception threshold:

$$\ddot{\Omega} = a_0\dddot{s} - a_1\dot{\Omega} - a_2\Omega\,,\ \ \Omega_t\,, \tag{2}$$

where $\dddot{s}$ is a linear acceleration derivative.

The model coefficients (1), (2) were determined by a parametric identification from results of flight tests [13]. Appropriate models were constructed along linear degrees of freedom

$$\begin{aligned}
&\ddot{\Omega}_x = \dddot{s}_x - 1{,}64\cdot\dot{\Omega}_x - 0{,}21\cdot\Omega_x\,,\ \ \Omega_{tx} = 0{,}23^{+0{,}10}_{-0{,}09}\,;\\
&\ddot{\Omega}_y = \dddot{s}_y - 1{,}64\cdot\dot{\Omega}_y - 0{,}25\cdot\Omega_y,\ \ \Omega_{ty} = 0{,}626^{+0{,}17}_{-0{,}17}\,;\\
&\ddot{\Omega}_z = \dddot{s}_z - 1{,}64\cdot\dot{\Omega}_z - 0{,}20\cdot\Omega_z\,,\ \ \Omega_{tz} = 0{,}16^{+0{,}020}_{-0{,}041}\,,
\end{aligned} \tag{3}$$

where x, y, z is longitudinal, vertical, lateral degree of freedom respectively,

and along angular degrees of freedom

$$\begin{aligned}
&\ddot{\Omega}_\gamma = 9{,}8\cdot\ddot{s}_\gamma - 10{,}06\cdot\dot{\Omega}_\gamma - 0{,}55\cdot\Omega_\gamma\,;\ \ \Omega_{t\gamma} = 2{,}65^{+0{,}68}_{-0{,}74}\,;\\
&\ddot{\Omega}_\psi = 9{,}8\cdot\ddot{s}_\psi - 10{,}11\cdot\dot{\Omega}_\psi - 1{,}10\cdot\Omega_\psi\,,\ \ \Omega_{t\psi} = 1{,}70^{+0{,}41}_{-0{,}48}\,,
\end{aligned} \tag{4}$$

where γ, ψ is roll and yaw respectively.

Due to finite process rate, motion cues have some time delays and able impede pilot's activity on flight simulator. There are two types of time delays.

Firstly, this is a transport delay (Fig. 2). Transport delay means a total flight simulator system processing time required for input signal from a pilot primary flight control until a motion system, visual system, or instrument response. It is the overall time delay incurred from input signal until output response. This time depends on used hardware and software. At early flight simulators the transport delay was 350 ms or more, which greatly impaired their efficiency. According to full flight simulators requirements [1], the transport delay should not exceed 150 ms.

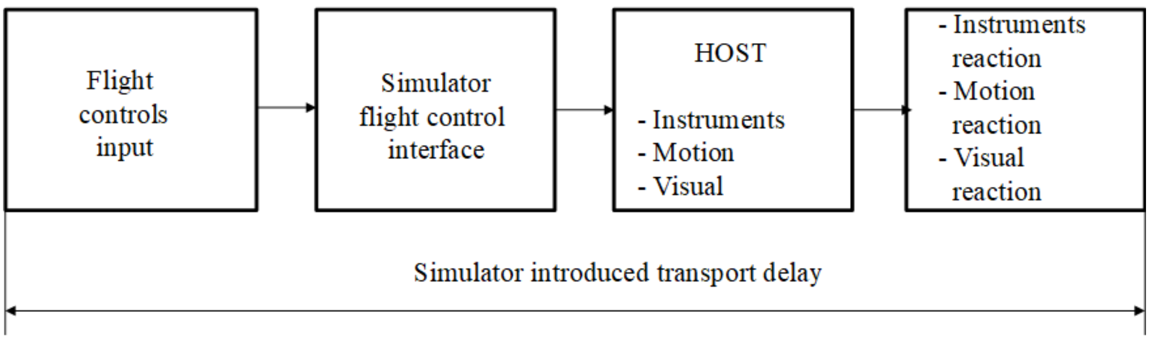

Fig. 2. Total simulator transport delay

Secondly, due to limitation of available constructive resources of motion system, it is impossible to continuously track an aircraft motion and direct use of motion perception models leads to appearance of false motion cues. So a simulator motion perception function can be differing from an aircraft motion perception function (Fig. 3). The aircraft motion perception function begins to differ from zero at the time $t = 0$. In the time t_2 an aircraft motion perception function reaches threshold and motion cue is perceived on aircraft.

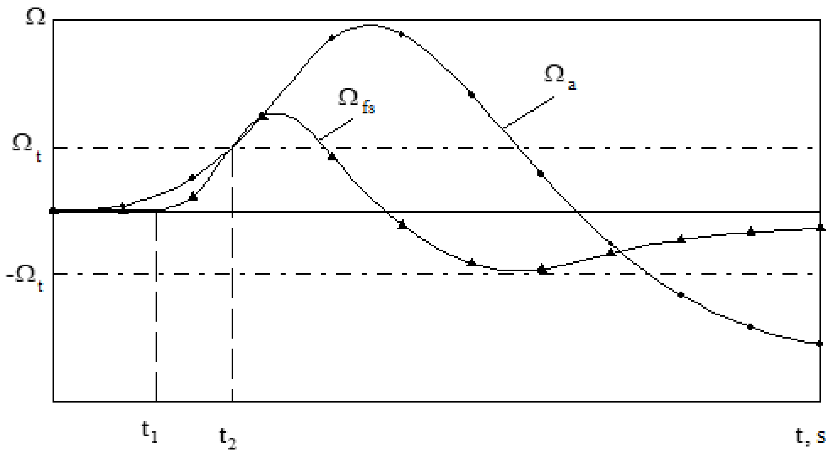

Fig. 3. Motion perception functions on aircraft and flight simulator

Formulation of purpose

In order to ensuring times of beginning motion perception on aircraft and full flight simulator it is necessary develop corresponding methodology of motion cueing along separate degrees of freedom.

Presentation of basic material

According to Gibson psycho-physiological perception theory [12] an internal representation of an external environment is based on characteristic features. The characteristic features of the dynamic motion cues are an initial time, a direction, an intensity and a duration of its perception. Connection between the motion cue and its characteristic features is essentially nonlinear. Taking into account the motion perception peculiarities it was formulated provisions, which serve as basis for creating of the high-fidelity motion cueing:

– characteristic signs of perceived motion cue should be simulated: initiative time, direction, intensity and duration of perception;
– character and direction of motion perception on flight simulator should be realistic;
– discrepancy between an initial time of motion perception on aircraft and flight simulator should meet flight simulator requirements;

– intensity and duration of motion cues on flight simulator should be proportional to intensity and duration of motion cues in real flight.

A forecast motion perception function $\bar{\Omega}_a$ (forecast values of motion perception aircraft function in time $t+\Delta\tau$) is calculated to ensure a coincidence of beginning time of motion cue perception on flight simulator and aircraft:

$$\bar{\Omega}_a = \Omega_a + \Delta\tau\dot{\Omega}_a + 0,5\Delta\tau^2\ddot{\Omega}_a.$$

A forecast time of aircraft motion perception function was determined along each degree of freedom during tests on the An-74TK-200 full flight simulator (Tab. 1.)

***Table* 1.**

Forecast time along separate degrees of freedom

Degree of freedom	longitudinal	vertical	lateral	roll	yaw
Forecast time, s	0,1	0,15	0,2	0,3	0,3

A perceived motion direction is described by sign of aircraft forecast motion perception function is calculated to determine a perceived motion intensity:

$$\bar{\dot{\Omega}}_a = \dot{\Omega}_a + \Delta\tau\ddot{\Omega}_a \, .$$

Traditionally, motion cue simulating when achieving of physical perception threshold with motion perception function. The necessary and sufficient condition for motion perception with physical threshold is described with achievement of aircraft forecast motion perception function module with physical threshold $|\bar{\Omega}_a| \geq \Omega_t$. The motion cueing with physical perception threshold showed that in certain situations, a motion cueing on full flight simulator occurs with a significant delay compared with motion perception on aircraft. Analysis of these situations showed that they did not take into account a motion perception with differential threshold. As latter it is understood that accept to the physical threshold of motion perception, there is the differential threshold, which consists in fact that after a motion perception with the physical threshold, a human distinguishes a motion cue intensity and perceives it as another motion cue, regardless of its sign. Experimentally values of the differential thresholds were determined on the An-74TK-200 full flight simulator along separate degrees of freedom (Tab. 2).

***Table* 2.**

The differential thresholds along separate degrees of freedom

Degree of freedom	longitudinal, m/s^4	vertical, m/s^4	lateral, m/s^4	roll, $degree/s^3$	yaw, $degree/s^3$
Differential threshold	0,15	2,5	1,5	2,5	0,5

The change of forecast motion perception function, which explains the movement perception with the physical threshold, is shown in Fig. 4. In this figure:

– point t_1 corresponds to the movement perception with the physical threshold,
– points t_2, t_4 of curves 4, 5 (these curves reflect the different nature of motion cue change over time) correspond to movement perception with the physical threshold with the opposite sign than at point t_1, and therefore motion cue will be simulated;
– point t_3 of curve 1 corresponds to movement perception with the physical threshold with the same sign as at point t_1, and due to insufficient design resource to simulate two or more consecutive motion cue of the same sign motion cue will not be simulated;
– points t_5, t_6 of curves 2, 3 correspond to movement perception with the physical threshold and since motion cue simulation perceived at point t_1 is completed, it is possible to simulate motion cue regardless of its sign.

The motion cueing with the differential threshold is as follows. In the case of motion perception with the differential threshold, a forecast motion perception function module exceeds the physical threshold and a derivative of forecast motion perception function module reaches the differential threshold (the previous derivative module of forecast motion perception function is less than the differential threshold, and a current forecast motion perception function is more than the differential threshold $\dot{\Omega}_t$) $\left|\dot{\bar{\Omega}}_a\right| \geq \dot{\Omega}_t$. These conditions are most commonly occurring in an aircraft motion along vertical and lateral degrees of freedom. The time history of motion perception function, which explains the formation of a beginning motion perception function with both physical and differential thresholds, is given in Fig. 4. In this figure:

– points $t_1, t_2, t_6, t_7, t_8, t_{10}, t_{11}$ of the curves 8, 1, 4, 5, 6 correspond to motion perception with the physical threshold;
– points t_3, t_5 of the curves 2, 3 correspond to a motion perception with the differential threshold;
– point t_4 of the curve 1 corresponds to a motion that is not perceived because, a motion perception function module is less than the physical threshold although a derivative module of motion perception function reaches the differential threshold;
– point t_9 of the curve 7 corresponds to a motion perception with the physical threshold, but motion cue is not simulated, since a motion perception function sign coincides with motion cueing sign.
– curve 2 corresponds to a motion that is not perceived by pilot, because motion perception function derivative module is not reached the differential

threshold although a motion perception function module is more than the physical threshold.

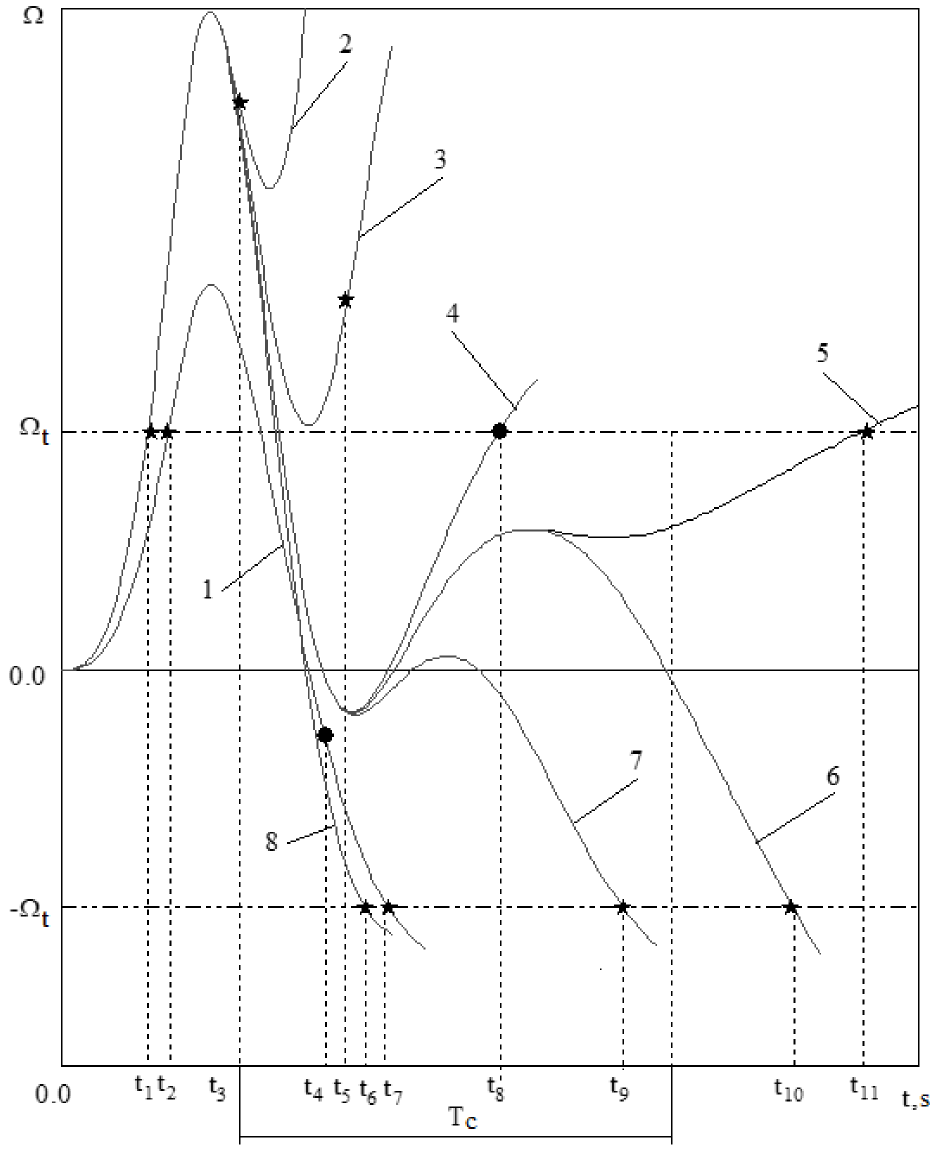

Fig. 4. Explanation of motion perception with both physical and differential thresholds

Conclusion

Developed method of motion cueing with both physical and differential threshold significantly increases the fidelity of motion cueing on full flight simulators of non-maneuvers aircraft. After this it is necessary to develop method of motion cueing along all aircraft degrees of freedom.

References

1. Manual of Criteria for the Qualification of Flight Simulation Training Devices. Doc. 9625 AN/938 – IKAO. 2015. – 680 p.

2. *Houshyar Asadi, Chee Peng Lim, Arash Mohammadi, Shady Mohamed, Saeid Nahavandi, Lakshmanan Shanmugam*. A genetic algorithm–based nonlinear scaling method for optimal motion cueing algorithm in driving simulator. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering **232**:8, 2018, - p. 1025-1038.
3. *R. C. Lemes, M. Moreira Souza, E. M. Belo, J. H. Bidinotto*. Latency on a Stewart platform using washout filter. The Aeronautical Journal **122**:1252, 2018, - p. 1003-1019.
4. *Zhou Fang, Andras Kemeny*. An efficient Model Predictive Control-based motion cueing algorithm for the driving simulator. *SIMULATION* **92**:11, 2016, - p. 1025-1033.
5. *Houshyar Asadi, Arash Mohammadi, Shady Mohamed, Chee Peng Lim, Amin Khatami, Abbas Khosravi, Saeid Nahavandi*. A Particle Swarm Optimization-based washout filter for improving simulator motion fidelity. *IEEE* International Conference on Systems, Man, and Cybernetics (SMC), 2016, - p. 001963-001968.
6. *Sergio Casas, Inmaculada Coma, Cristina Portalés, Marcos Fernández*. Towards a simulation-based tuning of motion cueing algorithms. Simulation Modelling Practice and Theory **67**, 2016, - p. 137-154.
7. *Tang Zhiyong, Ma Hu, Pei Zhongcai, Zhang Jinhui*. Adaptive motion cueing algorithm based on fuzzy tuning for improving human sensation. IEEE Chinese Guidance, Navigation and Control Conference (CGNCC), 2016, p. 1200-1205.
8. *Konrad Stahl, Klaus-Dieter Leimbach, Ansgar Meroth, Raoul Zollner*. A Washout and a Tilt Coordination Algorithm for a Hexapod Platform. *IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, - p. 1196-1201.
9. *Houshyar Asadi, Shady Mohamed, Delpak Rahim Zadeh, Saeid Nahavandi*. Optimisation of nonlinear motion cueing algorithm based on genetic algorithm. *Vehicle System Dynamics* **53**:4, 2015, - p. 526-545.
10. *Sergio Casas, Inmaculada Coma, Jose Vicente Riera, Marcos Fernandez*. Motion-Cuing Algorithms. Human Factors: The Journal of the Human Factors and Ergonomics Society **57**:1, 2015, - p. 144-162.
11. *Konrad Stahl, Gobir Abdulsamad, Klaus-Dieter Leimbach, Yuri A. Vershinin*. State of the art and simulation of motion cueing algorithms for a six degree of freedom driving simulator. 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), 2014, - p. 537-541.
12. *Gerlach O. H.* Developments in Mathematical Models of Human Pilot Behaviour// Aeronautical Journal. – 1977. – v. 81. – №799. – P. 293-305.
13. *Сотников Д. А., Кабанячий В. В.* Модели восприятия движения маневрирования самолета и их использование в задачах имитации движения на авиационных тренажерах// Безопасность полетов. – К.: КИИГА. – 1986. – С. 77-83.