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V. V. Kabanyachyi[1], – ORCID: https://orcid.org/0000-0003-0170-3923,
S. V. Hrytsan[2], – ORCID: https://orcid.org/0000-0002-4731-9292

METHODOLOGY OF LINEAR MOTION CUEING ON FLIGHT SIMULATORS

Ua Запропоновано метод вирішення задачі імітації акселераційних дій за лінійними степенями вільності на авіаційних тренажерах неманеврових повітряних суден. Він розроблений на основі характеристичних атрибутів сприйняття людиною акселераційних дій (за теорією сприйняття Гібсона: характер, напрямок, тривалість, інтенсивність та час сприйняття руху) та надає можливість покращити якість імітації лінійних акселераційних дій. Цей метод дає можливість, враховуючи існуючий конструктивний ресурс динамічного стенда, максимально наблизити імітовані акселераційні дії за лінійними степенями вільності до імітованих акселераційних дій у реальному польоті із однаковими керуючими діями. Завдяки цьому характер та напрямок імітованих акселераційних дій повністю відповідають реальним акселераційним діям, різниця між часом сприйняття акселераційних дій на літаку та тренажері мінімальна та відповідає сучасним вимогам. Тривалість та інтенсивність сприйняття акселераційних дій на тренажері пропорційні тривалості та інтенсивності сприйняття акселераційних дій на літаку. Такий метод імітації акселераційних дій значно покращує якість навчання та перепідготовки пілотів

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[1] *Igor Sikorsky Kyiv Polytechnic Institute*
[2] *Igor Sikorsky Kyiv Polytechnic Institute*

на авіаційних тренажерах.

En A method for solving the problem of motion cueing along linear degrees of freedom on flight simulators of non-maneuvering aircraft is proposed. It was developed on the basis of characteristic perception attributes of motion cues (according to Gibson’s perception theory: character, direction, duration, intensity and time of motion perception) and provides an opportunity to improve the quality of linear motion cueing. This method made it possible, taking into account the existing constructive resource of motion system, to bring as close as possible motion cueing along linear degrees of freedom on flight simulators to motion cues along linear degrees of freedom in real flight with the same control actions. Due to this the character and direction of motion cues fully correspond to the real motion cues, the difference between the perception time of motion cues on airplane and simulator is minimal and meets the current requirements. The duration and intensity of motion cue perception on simulator are proportional to duration and intensity of motion cue perception on airplane. Such method significantly improves the quality of training and retraining of pilots on flight simulators.

Introduction

Effective motion cueing on flight simulators is essential for training pilots and conducting research in aerospace engineering. Ensuring that flight simulators replicate the entire set of linear motion cues perceived by pilots on non-maneuvering aircraft a linear motion cueing is a crucial aspect of this endeavor. The ability to provide accurate motion cues enhances the fidelity of flight simulations, improving training outcomes and research validity.

The efficiency of flight simulators, which is expressed in adequacy of pilot's perception functions on flight simulators and aircraft, can be ensured only with information correspondence (similarity) between flight simulator and aircraft. The main difference between flight simulator and aircraft is the presence of computers in flight simulators, which requires solving fairly complex engineering problems and significant material costs. Due to economic limitations, flight simulators cannot provide complete physical modeling of aircraft dynamic properties in all channels of pilot perception, including motion cues.

According to the Gibson’s psychophysiological perception theory [1], internal representation of external environment is based on a set of characteristic features, perceived information about which is largely redundant. When processed by the brain, due to its increasing selectivity, this redundant information is successively reduced step by step. Only the necessary part of perceived information passes on, and less significant part is ignored. Due to process of information reduction, pilot's brain filters out from a significant volume of information about movement only that which is necessary for performing a specific piloting task.

Therefore, the current scientific problem is sintezing of flight simulator control cycle for creating motion cues that are as close as possible in its characteristic features (time of perception, direction, intensity and duration) to real ones.

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 the 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 behaviour. The motion-base geometry is established based on practical limitations, as well as criteria for platform stability 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 hydraulic cylinders 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 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 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 model framework 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 location angles in space of the Stewart platform, under which condition of stable equilibrium operation of the Stewart platform is met.

A set of characteristic perception attributes of motion cues is determined [12]. Based on the system approach principles, the mathematical formulation of the motion cueing problem along linear 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.

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 linear degrees of freedom is actual.

Problem statement

The purpose of this study is to develop an effective method of motion cueing along linear degrees of freedom on non-maneuvering aircraft. This is necessary due to high cost of motion system and growing requirements for motion cues fidelity. Perception of motion cueing should be so close as possible to perception of real motion cues.

Presentation of basic material

To evaluate motion cues perceived by pilot, it is necessary to use as a criterion a functional that evaluates error in coincidence of motion cue perception on flight simulator and aircraft:

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

where Ω_a, Ω_{fs} are motion perception function on flight simulator and aircraft, respectively,

Ω_t is motion perception threshold,

$u(t)$ is control vector,

and the problem of motion cueing is reduced to control synthesis that minimizes the functional:

$$\begin{aligned} & J(u) = min \Rightarrow u(t) \\ & s \in s^* \\ & q \in \Omega_q \\ & sign\Omega_{fs} , \end{aligned}$$

where s is motion system movement;

s^* is limited working range of motion system movement;

q is vector of motion system characteristics;

Ω_q is determining permissible domain of motion system characteristics, i.e. domain within which the standardized quality of motion system movement is ensured.

The developed methodology is based on the method which was proposed [13] for synthesizing program signals with feedback. For a sufficiently simple synthesis of program signals, the set of feasible solutions was narrowed and program signals were sought in polynomial form:

$$u=\sum_{i-1}^{m} c_i,\ \tau^{i}$$

where m is number of program signal parameters;

c_i is i-th program signal parameter;

τ is current time of program signal.

To select the optimal trajectory for transferring motion system from the initial phase state to the final one, the optimality criterion was used,

$$J=\frac{1}{2}\int_{0}^{T}u^{2}dt,$$

where T is control interval duration.

The optimum is ensured due to the fact that the number of final conditions is equal to the system order.

To transfer the motion system during time T from the initial phase state $\left\{s_0^{(\nu)}, \nu=\overline{0,n}\right\}$ to the final one $\left\{s_k^{(\nu)}, \nu=\overline{0,n}\right\}$, the control is used

$$u=\sum_{j=0}^{r+n-1}k_j\tau^{j}+\sum_{\nu}^{r-1}k_{s\nu}s^{(\nu)},$$

where $k_j=\sum_{j=0}^{r+n_1}\frac{r!(r+n-\nu-1)!}{j!(r-\nu)!\nu!\Delta T^{r-\nu}}s_0^{(j+\nu)},\ j=\overline{0,r+n-1}$ are coefficients of program signal

$k_{s\nu}=\frac{r!(r+n-\nu-1)!}{(r-\nu)!\nu!\Delta T^{r-\nu}},\ \nu=\overline{0,r-1}$ are coefficients of additional feedback.

The program signal is a function of time and current phase coordinates of motion system,

$$u=f(\tau)+f(s),$$

where $f(\tau)$ is program signal component;

$f(s)$ is feedback component.

The developed synthesis of program signals is applicable only to linear systems and does not take into account the restrictions on current phase coordinates and controls. Motion system is adequately described by a second-order differential equation with constant coefficients and the requirement to maintain its characteristics within normalized limits significantly limits nonlinear distortions, value of which is at least an order of magnitude less than useful signals and which can be neglected. Motion cueing involves the synthesis of program signals using analytical relationships between real aircraft motion and desired program motion of motion system. To take into account constraints on current phase coordinates and control, control cycle is divided into seven stages so that the constraints fall on boundaries of control subintervals:

1. acceleration stage, at which the value of motion system acceleration derivative is reached;
2. tracking stage, at which the motion system acceleration derivative is constant and equal to the acceleration derivative;
3. transition to stabilization stage, at which the value of motion system stabilization acceleration is reached;
4. stabilization stage, at which the motion system acceleration is constant and equal to the stabilization acceleration;
5. transition to braking stage, at which the motion system braking acceleration is reached;
6. braking stage, at which motion system is braked to a stop;
7. return stage, at which motion system returns to its original position.

Let us consider the formation of the control cycle stages (Fig. 1).

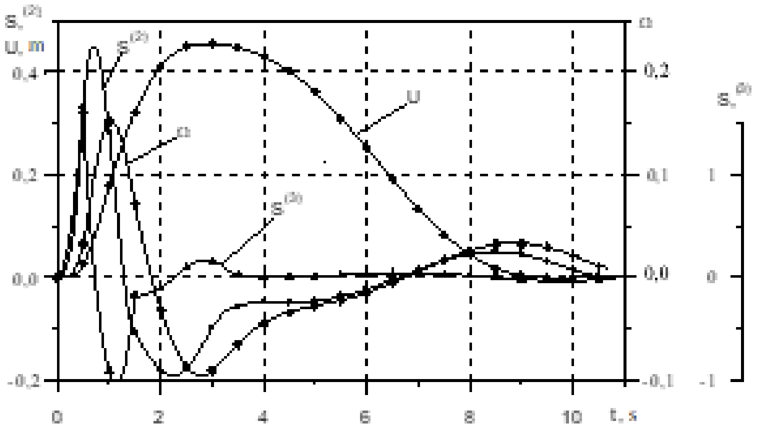

Fig. 1. Phase coordinates changing of motion system and program signal during motion cueing

Acceleration stage. At the acceleration stage, motion system starts moving from the initial position and at the end of the stage, the acceleration derivative program is reached $\bar{s}_1^{(3)}$: $s_{k1}^{(3)} = \bar{s}_1^{(3)}$. To exclude occurrence of false motion cues, condition of maintaining a constant sign of fourth derivative of motion system movement over time must be met: $sing s^{(4)} = \text{const}$. To meet this condition, the following program for phase coordinates changing of motion system is set at the acceleration stage:

$$s^{(4)} = \bar{s}_1^{(5)}\tau_1, \;\; \tau_1 \in [0, T_1],$$

$\bar{s}_1^{(5)}$ is the program fifth derivative of motion system movement over time of the acceleration stage;

τ_1 is current time;

T_1 is duration of the acceleration stage.

The program signals at the acceleration stage:

$$u^{(2)} = s^{(2)} + \left(b_{m2} \cdot s^{(3)} + s^{(4)} \cdot \tau_1\right) \Big/ b_{m1},$$

where b_{m1}, b_{m2} are the coefficients of motion system model.

Tracking stage. At the tracking stage, a constant value of the motion system acceleration derivative specified by the program acceleration derivative is maintained:

$$s^{(3)} = \bar{s}_1^{(3)}, \tau_2 \in [0, T_2],$$

where $s^{(3)}$, $\bar{s}_1^{(3)}$ are current and program derivatives acceleration of motion system at the tracking stage, respectively;

τ_2 is current time;

T_2 is duration of the tracking stage.

Program signal at the tracking stage:

$$u^{(2)} = s^{(2)} + b_{m2} \cdot s^{(3)} / b_{m1}.$$

Stage of transition to stabilization. At the end of the transition to stabilization stage, motion system acceleration must reach the specified acceleration value, and the derivative acceleration of motion system must be equal to zero. To prevent occurrence of false motion cues, the condition of maintaining a constant sign of the fourth derivative of motion system displacement must be met $sings^{(4)} = const$. Fulfillment of this condition is ensured by the motion system program:

$$u^{(2)} = \left(b_{m1} \cdot s^{(2)} + b_{m2} \cdot s^{(3)} + s_{03}^{(4)} + s_3^{(5)} \cdot \tau_3\right) \Big/ b_{m1}.$$

Stage of stabilization. At the stabilization stage, condition of maintaining a constant value of motion system acceleration, which is specified by the motion system motion program, is met: $u^{(2)} = s^{(2)}$.

Stage of transition to braking. At the transition to braking stage, the final phase coordinates of motion system must be reached. To meet the condition of maintaining a constant sign of fourth derivative of motion system displacement, the motion program is set:

$$s^{(4)} = s_{05}^{(4)} + \bar{s}_5^{(5)} \tau_5, \ \tau_5 \in [0, T_5],$$

where $s_{05}^{(4)}$ is the initial fourth derivative of motion system displacement at the transition to braking stage;

$\bar{s}_5^{(5)}$ is the program fifth derivative of motion system movement at the stage of transition to braking;

τ_5 is current time of the transition to braking stage;

T_5 is duration of the transition to braking stage.

To synthesize a program signal with optimal response time, duration of the stage is determined from the condition of the functional minimum:

$$J = \frac{1}{2}\int_0^T u^2 dt .$$

The program signal is calculated using the formula:

$$u^{(2)} = \left(\begin{matrix} k_0 + k_1\tau_5 + k_2\tau_5^2 + k_3\tau_5^3 + k_4\tau_5^4 + k_5\tau_5^5 + k_6\tau_5^6 + k_7\tau_5^7 - \\ -d_{s0}s^{(0)} - d_{s1}s^{(1)} - d_{s2}s^{(2)} - d_{s3}s^{(3)} \end{matrix} \right) \Bigg/ b_{m1} ,$$

where $d_{s0} = k_{s0}$, $d_{s1} = k_{s1}$, $d_{s2} = k_{s2} + b_{м1}$, $d_{s3} = k_{s3} + b_{м2}$ are additional feedback coefficients.

Braking stage. At the end of the braking stage, motion system movement must be equal to the movement working range, and the remaining phase coordinates must be zero. At this stage, the condition of maintaining a constant value of the motion system acceleration, which is specified by motion program, is met: $u^{(2)} = s^{(2)}$.

Return stage. At the end of the return stage, the phase coordinates of motion system must be zero. Duration of the return stage is determined from the equation:

$$f(T_7) = T_7^4 - \frac{1}{\bar{s}_7^{(5)}} \sum_{\nu=0}^{3} k_{s\nu} s^{(\nu)} T_7^{\nu} = 0 ,$$

where $\bar{s}_7^{(5)}$ is the program fifth derivative of motion system movement at the return stage,

T_7 is duration of the return stage.

This equation is solved by the Newton-Kantorovich method [14]:

$$T_7 = T_{7-} - f(T_{7-}) / f'(T_{7-}) ,$$

where T_{7-} is the previous value of duration of the return stage,

$$f'(T_7) = 4T_{7-}^3 - \frac{1}{\bar{s}_7^{(5)}} \sum_{\nu=0}^{3} i k_{s\nu} s^{(\nu)} T_{7-}^{(\nu-1)} .$$

The calculation is completed when the condition is met: $|T_7 - T_{7-}| < 10^{-4}$. The program signal is calculated using the formula:

$$u^{(2)} = \left(\begin{matrix} k_0 + k_1\tau_7 + k_2\tau_7^2 + k_3\tau_7^3 + k_4\tau_7^4 + k_5\tau_7^5 + k_6\tau_7^6 + k_7\tau_7^7 - \\ -d_{s0}s^{(0)} - d_{s1}s^{(1)} - d_{s2}s^{(2)} - d_{s3}s^{(3)} \end{matrix} \right) \Bigg/ b_{m1} .$$

Since the durations of the tracking, transition to stabilization and stabilization stages are not preliminarily determined, they are determined in the process of program signal synthesizing and depend on the current and program phase coordinates, then in the general case a control cycle is open in time. To obtain a closed control cycle, the values of the phase coordinates of the control cycle stages are specified, ensuring the creation of motion cue of the desired intensity and duration. The duration of the control cycle, which depends on the initial phase state of motion system, the specified constraints and the desired values of phase coordinates, is determined using the formula:

$$T_c = \sum_{i=1}^{7} T_i \ ,$$

where T_i is duration of the i-th stage.

Research results

Based on the system approach, the method has been developed in which:

- control with feedback along all phase coordinates is used, which transfers motion system during a given time to a given phase point;
- program signal is a function of time and current phase coordinates of motion system, includes a program component and a feedback component, which ensures that motion system is maintained on a given phase trajectory, and has an adjustable degree of binding to program phase trajectory;
- real dynamic characteristics and available design resources of motion system and features of motion cue perception are taken into account.

Motion cueing is based on synthesis on the basis of analytical relationships between the parameters of aircraft cabin movement and the desired motion system movement, of program signals that ensure such motion system movement from the initial phase state to the final one, so that motion cues are perceived as reaction of aircraft to the corresponding control or disturbing action. Optimum is ensured by the fact that the number of final conditions is equal to the order of system.

The program signal combines the law properties of different classes:

- is a law of final control and transfers motion system to a given phase point in a given time;
- has feedback on all phase coordinates, which ensures that motion system is kept on the phase trajectory;
- has an adjustable degree of binding to program phase trajectory.

To ensure the necessary change smoothness in motion cues and avoid the imitation of false motion cues, the highest derivative describing motion cue perception is used as a program signal. To take into account the restrictions on the current phase coordinates and control, the control cycle that provides motion cueing is divided into components in such a way that restrictions fall on boundaries of control subintervals: acceleration stage, tracking stage, transition to stabilization stage, stabilization stage, transition to braking stage, braking stage, return stage.

Conclusion

A method for solving the problem of motion cueing along linear degrees of freedom on flight simulators of non-maneuvering aircraft was developed on the basis of characteristic perception attributes of motion cues (according to Gibson's perception theory: character, direction, duration, intensity and time of motion perception) and provides an opportunity to improve the quality of linear motion cueing. This method made it possible, taking into account the existing constructive resource of motion system, to bring as close as possible motion cueing along linear degrees of freedom on flight simulators to motion cues along linear degrees of freedom in real flight with the same control actions. Due to this the character and direction of motion cues fully correspond to the real motion cues, the difference between the perception time of motion cues on airplane and simulator is minimal and meets the current requirements. The duration and intensity of the motion cue perception on simulator are proportional to duration and intensity of motion cue perception on airplane. Such method significantly improves the quality of training and retraining of pilots on flight simulators.

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