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PROBLEM OF LOW-FREQUENCY MOTION CUEING ALONG ROLL ON FLIGHT SIMULATORS

Ua Представлено інноваційний підхід до підвищення точності низькочастотної імітації поперечних акселераційних дій на комплексних тренажерах неманеврових літаків. На основі особливостей сприйняття вестибулярною системою людини руху за креном сформульовано та розв'язано задачу імітації поперечних акселераційних дій системами рухомості авіаційних тренажерів. Вирішено критичне завдання імітації набору кутових акселераційних дій, які пілоти сприймають під час польотів. Це дослідження підкреслює два ключові результати. Фільтр низьких частот четвертого порядку ефективно виділяє низькочастотні акселераційні дії з кінематичних параметрів руху літака, підвищуючи точність імітації. По-друге, запропонований метод значно розширює діапазон імітованих акселераційних дій, одночасно забезпечуючи їхню синхронізацію з високочастотними акселераційними діями вздовж відповідних степенів вільності. Така постановка задачі збільшує діапазон імітованих акселераційних дій до $\pm 0{,}3n_z$, що практично відповідає діапазону імітованих акселераційних дій транспортного літака, і таким чином підвищує якість імітації акселераційних дій. Реалізація розробленого методу на комплексному тренажері літака Ан-72ТК-200 підтвердила його ефективність. На завершення це дослідження представляє багатообіцяючу методологію, яка покращує якість імітації акселераційних дій, таким чином роблячи імітацію акселераційних дій більш реалістичною та корисною як для пілотів, так і для дослідників аерокосмічної техніки на реальних авіаційних тренажерах неманеврових літаків.

En An innovative approach to improve the fidelity of low-frequency lateral motion cueing within full-flight simulators for non-maneuvering aircraft is presented. On the basis of the perception peculiarities by the human vestibular system of movement along the roll, the problem of low-frequency motion cueing of lateral movement by motion systems of flight simulators was formulated and solved. The critical challenge of simulating the set of angular motion cues that pilots perceive during flights is decided. This research highlights two key outcomes. The fourth-order low-pass filter effectively extracts low-frequency motion cues from aircraft motion kinematic parameters, enhancing simulation accuracy. Secondly, proposed method significantly expands the range of simulated motion cues while ensuring their synchronization with high-frequency motion cues along relevant degrees of freedom. This formulation of the problem increases the range of simulated motion cues to $\pm 0{,}3n_z$, which practically corresponds to the range of simulated motion

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cues of a transport aircraft, and thus increases the quality of motion cueing. The implementation of the developed method on the An-72TK-200 full flight simulator confirmed its effectiveness. In conclusion, this study introduces a promising methodology that enhances the quality of motion cueing, thus rendering flight simulations more realistic and beneficial for both pilots and aerospace engineering researchers in the real of non-maneuvering aircraft flight simulators.

Introduction

The motion system is a mandatory component of Full flight simulators (FFS) [1], [2], [3]. Angular motion cueing, in particular along roll, is an important component of the motion system [1], [2], [3]. That is why all the first flight trainers, including the Link Trainer, simulated motions only along angular degrees of freedom.

Statement of problem

That is why all the first flight trainers, including the Link Trainer, simulated motions only along angular degrees of freedom.

The ability to provide accurate motion cues enhances the fidelity of flight simulations, improving training outcomes and research validity. Modern six degrees-of-freedom synergetic motion system (6DOF) allow motion cueing without distortion only a certain range of low-frequency motion cues. In order to increase the range of simulated motion cues and increase quality of motion cueing on FFS the action of the gravity component can be used.

If the FFS cabin is tilted in roll, as shown in Fig. 1, the gravity component can provide lateral motion cues for the flight crew, provided that the flight crew are unaware that the cabin has been rotated in roll. For example, if the cabin is titled to 45◦, then the flight crew will experience a continuous lateral acceleration of 0,7 G.

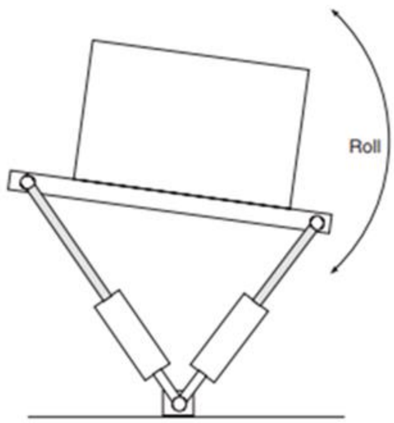

Fig.1. Motion system angular movement (side view)

The basis for this is the peculiarity of human perception of linear movements. Vestibular system reaction to linear movements, which do not distinguish between active forces and gravity. By tilting the motion system (Fig. 2) at such an angle to the local gravity vertical $\gamma = \arcsin\left(\ddot{s}_{az} / g\right)$ that the analyzers of the pilot's vestibular system perceive the resulting overload with the same relative orientation as in real flight, simulate low-frequency motion cues in a fairly wide range.

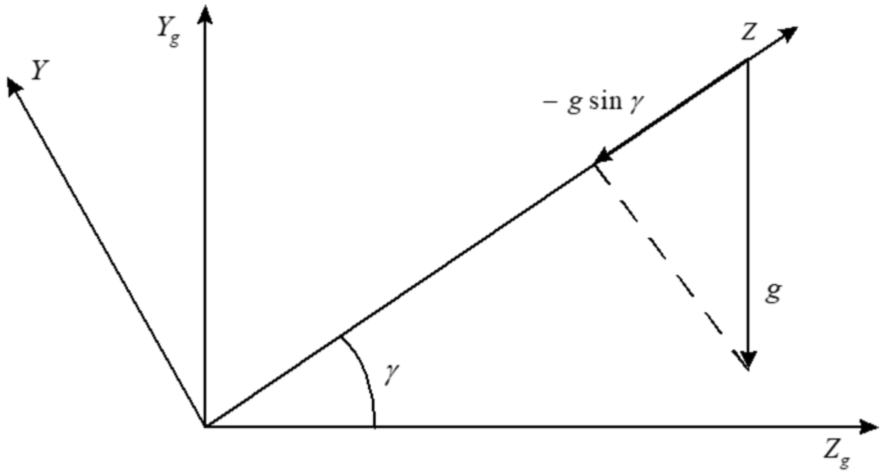

Fig. 2. Low-frequency motion cueing

Low-frequency motion cues are extracted by low-frequency filters of the second order. The input signals of these filters are lateral aircraft accelerations, and the output signals are roll angles. Since the angular movement can be considered proportional to the simulated acceleration, the filter input signal in the form of the motion system movement is determined based on the range of simulated motion cues. Disadvantages of this procedure for low-frequency motion cueing are due to the lack of proper consistency with high-frequency motion cueing. This leads to a violation of the perception of the aircraft spatial movement and negative assessments by pilots in general. In addition, the passage of aircraft accelerations through filters causes their distortion and can lead to the appearance of false motion cues.

While low-frequency motion cueing, restrictions are imposed on the magnitude and nature of the change in the motion system position:

The motion system inclination angle should be small enough so as not to cause the appearance of perceived false motion cues along other degrees of freedom (in this case, along the lateral degree of freedom $-mg\sin\gamma < m\ddot{s}_{zt}$, where $\ddot{s}_{zt}$ is the threshold of human sensitivity to lateral acceleration.

False motion cues may appear along the roll, which are not present in the real flight and which are caused by the motion system movement along the roll. The last circumstance imposes a limit on the speed along roll. To successfully apply the method of motion system coordinated tilt and avoid the appearance of false motion cues, the motion system angular movement is carried out at such a speed that the pilot does not feel it and does not detect the motion system turning, that is, less than the threshold value. This means that only low-frequency motion cues can be simulated by the motion system slope.

Modern DOF6 allow to simulate the roll motion cues of non-maneuvering aircraft with almost no distortion. However, this approach is not rational due to the fact that at the same time as motion cueing along roll, the pilot can perceive motion cue by other degrees of freedom. On the other hand, perception of motion cues along angular degrees of freedom corresponds to the perception of similar aircraft motion cues only in a certain range of motion system angles. And motion system angles greater than this range are perceived (due to the absence of the summation effect) as not corresponding to aircraft angles (larger). Therefore, when low-frequency motion cueing, the motion system angles repeat the aircraft angles up to a certain value, and then the motion cues are simulated with slightly smaller motion system angles.

Analysis of last achievements and publications

Many investigations [4 – 12] of motion cueing were conducted in order to increase a 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 movement. On the other hand, only motion perception is important for pilot. Therefore, during motion cueing, it is important not movement of motion system itself, but created motion cues and how much their perception on flight simulator corresponds to real ones with same control actions.

Work [4] presents the development of motion cueing algorithms (MCAs) that uses the optimal trajectory of an open-loop, optimization-based MCA as a reference in a closed-loop simulation. Deviations between closed-loop driver and the reference are compensated by a closed-loop, state-of-the-art MCA. By combining a closed-loop MCA with the predictions obtained by an open-loop MCA, a hybrid motion cueing algorithm is obtained.

Article [5] focuses on the current motion simulators' structural designs and working principles alongside the currently developed motion control algorithms to achieve the highest fidelity. Furthermore, some suggestions are made for future works which it is believed are worth investigating to provide robustness and adaptively to the control of simulation systems, improving their fidelity and realism alongside reducing motion sickness experienced by the simulator operator.

Paper [6] presents a nonlinear Multimedia Personal Computer (MPC) - based algorithm which incorporates the nonlinear kinematics of the Stewart platform within the MPC algorithm in order to increase the cueing fidelity and use maximum workspace. Furthermore, adaptive weights-based tuning is used to smooth the movement of the platform towards its physical limits. Full-track simulations were carried out and performance indicators were defined to objectively compare the response of the proposed algorithm with classical washout filter and linear MPC-based algorithms. The results indicate a better reference tracking with lower root mean square error and higher shape correlation for the proposed algorithm.

As shown in [7] testing with real prototype vehicles takes significant time and can pose risks for the test. By utilizing cutting edge motion platform-based simulators, these drawbacks can be significantly reduced or completely eliminated.

Advances in technology are resulting in a steady improvement in the fidelity and the effectiveness of simulators [8]. In modern simulators the motion generation system is one of the major subsystems employed to create realistic virtual worlds. Recent hardware developments have improved the fidelity of these motion systems significantly.

In paper [9], a novel optimal motion cueing algorithm is developed to reduce the false cues from system sensing lateral tilted angle. The optimal motion cueing algorithm has a significant effect on the pilot's perception when the tilted angle is rather large. Several objective criteria were introduced to evaluate the simulated perception of all investigated motion cueing algorithms.

It is proposed [10] sliding mode-based cueing algorithm, which makes the simulator to slide in close proximity across the boundary of workspace. The experimental results give evidence of a 57% increase in the considered sub-workspace, thereby reducing the relative necessity to saturate the motions as compared to classical motion cueing algorithm. This leads to a better experience of a user enjoying scenario. On the other hand, the following drawbacks are reported: (1) necessity to analytically model the workspace boundary and ensuring that it is smooth with nonzero gradient, (2) sliding mode-based cueing algorithm parameter selection is more cumbersome than classical motion cueing algorithm, thereby making its utility restricted to recorded scenarios.

The studies [11] consider the constraints in the Cartesian coordinate system of the hexapod mechanism, instead of its design parameters. This consideration results in a poor usage of the hexapod workspace due to the conservative assumptions; consequently, the simulation-based motion platform users do not experience realistic motions. The main contribution of this article is to take the simulation-based motion platform's physical limitations into account in the model predictive control model such that more precise motion cues can be extracted for the users. A linear time-varying model predictive control-based simulation-based motion platform method is designed for the first time in this article to consider the parameters of the hexapod mechanism in the model predictive control model.

The object of research [12] is motion cueing along angular degrees of freedom on flight simulators of non-maneuvering aircraft. Based on the system approach principles, the mathematical formulation of the solution to the problem of motion cueing along angular degrees of freedom on flight simulators of non-maneuvering aircraft is used. Such approach made it possible, taking into account the existing constructive resource of flight simulator motion system, to bring as close as possible motion cueing along angular degrees of freedom on flight simulators of non-maneuvering aircraft to motion cues along angular degrees of freedom in real flight with the same control actions.

Formulation of purpose

Due to high cost of motion system and growing requirements for motion cues fidelity, it is necessary to develop an effective method of motion cueing on non-maneuvering aircraft along roll angular degrees of freedom for improving the fidelity of low-frequency lateral motion cueing.

Presentation of basic material

The following procedure was developed to low-frequency lateral motion cueing. First of all, it is considered that motion cues along the lateral degree of freedom are perceived by the pilot only when the motion perception function reaches the perception threshold

$$(\Omega_z(\geq \Omega_{tz} .$$

And the perception of motion cue disappears when the motion perception function falls below the perception threshold

$$(\Omega_z(< \Omega_{tz} .$$

The motion system roll angle, simulating the low-frequency perceived lateral motion cues, is calculated as the output signal of the fourth-order low-pass filter (the filter of this order was chosen because, in order to avoid the appearance of false high-frequency motion cues, it is necessary to take into account the restrictions on the derivatives of the motion system roll angle in time up to the fourth order inclusive):

$$\gamma_{z1}^{(4)} = b_{\gamma 10}(\ddot{s}_{az} - \gamma_{z1}) - b_{\gamma 11}\dot{\gamma}_{z1} - b_{\gamma 12}\ddot{\gamma}_{z1} - b_{\gamma 13}\dddot{\gamma}_{z1} \quad , \qquad (1)$$

where $\gamma_{z1}^{(4)}$, $\dddot{\gamma}_{z1}$, $\ddot{\gamma}_{z1}$, $\dot{\gamma}_{z1}$ are the fourth-, third-, second-, and first-time derivatives of the motion system roll angle, which simulates low-frequency perceived lateral motion cue;

γ_{z1} is the motion system roll angle, which simulates the perceived low-frequency lateral motion cue;

$b_{\gamma 10}$, $b_{\gamma 11}$, $b_{\gamma 12}$, $b_{\gamma 13}$ are the coefficients of the fourth-order filter, which determine motion system roll angle, simulated the perceived low-frequency lateral motion cue:

$$\left[b_{\gamma 10}, b_{\gamma 11}, b_{\gamma 12}, b_{\gamma 13}\right] = \left[\frac{840}{\Delta T_{\gamma z1}^{4}}; \frac{480}{\Delta T_{\gamma z1}^{3}}; \frac{120}{\Delta T_{\gamma z1}^{2}}; \frac{16}{\Delta T_{\gamma z1}}\right],$$

where $\Delta T_{\gamma z1}$ is the time constant of the fourth-order filter, which determines motion system roll angle, simulated the perceived low-frequency lateral motion cue.

The motion system roll angle, which simulates low-frequency nonperceived lateral motion cues, is calculated as the output signal of the fourth-order low-pass filter:

$$\begin{gathered}\gamma_{z2}^{(4)} = b_{\gamma 20}\gamma_{z2} - b_{\gamma 21}\dot{\gamma}_{z2} - b_{\gamma 22}\ddot{\gamma}_{z2} - b_{\gamma 23}\dddot{\gamma}_{z2}\gamma_{z2}^{(4)} = b_{\gamma 20}\gamma_{z2} - b_{\gamma 21}\dot{\gamma}_{z2} - \\ - b_{\gamma 22}\ddot{\gamma}_{z2} - b_{\gamma 23}\dddot{\gamma}_{z2},\end{gathered} \quad , \qquad (2)$$

where $\gamma_{z2}^{(4)}$, $\dddot{\gamma}_{z2}$, $\ddot{\gamma}_{z2}$, $\dot{\gamma}_{z2}$ are the fourth-, third-, second-, and first-time derivatives of the motion system roll angle, which simulates unperceived low-frequency lateral motion cue;

γ_{z2} is the motion system roll angle, which simulates unperceived low-frequency lateral motion cue;

$b_{\gamma 20}, b_{\gamma 21}, b_{\gamma 22}, b_{\gamma 23}$ are the coefficients of the fourth-order filter, which determine motion system roll angle, simulated unperceived low-frequency lateral motion cue:

$$\left[b_{\gamma 20}, b_{\gamma 21}, b_{\gamma 22}, b_{\gamma 23}\right] = \left[\frac{840}{\Delta T_{\gamma z2}^{4}}; \frac{480}{\Delta T_{\gamma z2}^{3}}; \frac{120}{\Delta T_{\gamma z2}^{2}}; \frac{16}{\Delta T_{\gamma z2}}\right],$$

where $\Delta T_{\gamma z2}$ is the time constant of the fourth-order filter, which determines motion system roll angle, simulated unperceived low-frequency lateral motion cue.

The motion system roll angles, which simulate both perceived and unperceived low-frequency lateral motion cues, are determined by integrating Equation 1 and Equation 2. Considering the above, the program signal for simulating low-frequency motion cues $u_{\gamma z}$ is equal to:

– zero (low-frequency motion cues are not simulated) in the absence of perceived and simulated motion cue ($u_{\gamma z} = 0,\ \delta_z = 0$);

– motion system roll angle γ_{z1} (low-frequency motion cue is simulated):
when the motion perception function reaches the perception threshold ($u_{\gamma z} = 0,\ \delta_z = 1$),
at the perceived lateral motion cue ($u_{\gamma z} \neq 0, \left(\Omega_z \left(\geq \Omega_{tz} \right),\right.$

– provided there is no perceived lateral motion cue and perceived roll angle $\left(u_{\gamma z}\left(\geq \varepsilon_\gamma, (\Omega_z(< \Omega_{tz}\right);$
– motion system roll angle γ_{z2} (motion system returns to its initial position), if neither the lateral motion cue nor the motion system roll angle are perceived ($0 < \left(u_{\gamma z}\left(< \varepsilon_\gamma, (\Omega_z(< \Omega_{nz}\right)$:

$$u_{\gamma z} = \begin{cases} 0 & \left| u_{\gamma z} = 0,\ \delta_z = 0; \right. \\ \gamma_1 & \left| \begin{array}{l} u_{\gamma z} = 0,\ \delta_z = 1; \\ u_{\gamma z} \neq 0,\ |\Omega_z| \geq \Omega_{\text{tz}}; \\ |u_{\gamma z}| \geq \varepsilon_\gamma,\ |\Omega_z| < \Omega_{\text{tz}}; \end{array} \right. \\ \gamma_2 & \left| 0 < |u_{\gamma z}| < \varepsilon_\gamma,\ |\Omega_z| < \Omega_{\text{tz}}, \right. \end{cases} \tag{3}$$

where ε_γ is the rollback threshold.

The program signal for low-frequency lateral motion cueing and high-frequency roll motion cueing is calculated by the formula:

$$u_{\gamma\Sigma} = u_\gamma + u_{\gamma z}\,, \tag{4}$$

where u_γ is the program signal for high-frequency roll motion cueing.

In order for the motion system roll angle to be within the operating range, a program signal is calculated to low-frequency lateral motion cueing and high-frequency roll motion cueing, taking into account the restrictions $\bar{u}_{\gamma\Sigma}$:

$$\bar{u}_{\gamma\Sigma} = \begin{cases} -0{,}5a_\gamma(\gamma_{\Sigma 2} - \gamma_{\Sigma 1}) & \left| u_{\gamma\Sigma} \leq -\gamma_{\Sigma 2}; \right. \\ a_\gamma \left[u_{\gamma\Sigma} - \dfrac{\left(u_{\gamma\Sigma} - \gamma_{\Sigma 1}\right)^2}{2\left(\gamma_{\Sigma 1} - \gamma_{\Sigma 2}\right)} \right] & \left| -\gamma_2 < u_{\gamma\Sigma} < \gamma_{11}; \right. \\ a_\gamma u_{\gamma\Sigma} & \left| \gamma_1 \geq |u_{\gamma\Sigma}|; \right. \\ a_\gamma \left[u_{\gamma\Sigma} - \dfrac{\left(u_{\gamma\Sigma} - \gamma_{\Sigma 1}\right)^2}{2\left(\gamma_{\Sigma 2} - \gamma_{\Sigma 1}\right)} \right] & \left| \gamma_2 > u_{\gamma\Sigma} > \gamma_{\Sigma 1}; \right. \\ 0{,}5a_\gamma(\gamma_{\Sigma 2} - \gamma_{\Sigma 1}) & \left| u_{\gamma\Sigma} \geq \gamma_{\Sigma 2}, \right. \end{cases} \tag{5}$$

where $\gamma_{\Sigma 2}$ is the maximum aircraft roll angle of the, simulated by the motion system roll angle;

a_γ is transmission coefficient for both low-frequency lateral motion cuing and high-frequency roll motion cueing, taking into account the restrictions:

$$a_\gamma = \begin{cases} 1 & \left|\gamma^* > \gamma_{\Sigma 2};\right. \\ \dfrac{2\gamma^*}{\gamma^* - \gamma_{\Sigma 2}} & \left|\gamma^* \le \gamma_{\Sigma 2},\right. \end{cases} \qquad (6)$$

where $\gamma_{\Sigma 1} = \dfrac{2 \cdot \gamma}{a_\gamma} - \gamma_{\Sigma 2}$ is the aircraft roll angle, which corresponds to the inflection point of the dependence of the aircraft roll angle on the aircraft roll angle.

As can be seen from Fig. 3, in the range of roll angles $[-\gamma_{\Sigma 1}, \gamma_{\Sigma 1}]$, the program signal along roll with restrictions is equal to the aircraft roll angle, in the range of roll angles $[-\gamma_{\Sigma 2}, -\gamma_{\Sigma 1}]$ and the dependence of the program signal with restrictions on the aircraft roll angle $[\gamma_{\Sigma 1}, \gamma_{\Sigma 2}]$ is nonlinear, and in the ranges beyond the maximum simulated aircraft roll angle, the program signal along roll with restrictions remains constant and equal to the positive γ or negative $-\gamma$ value of the working range of the motion system roll, respectively.

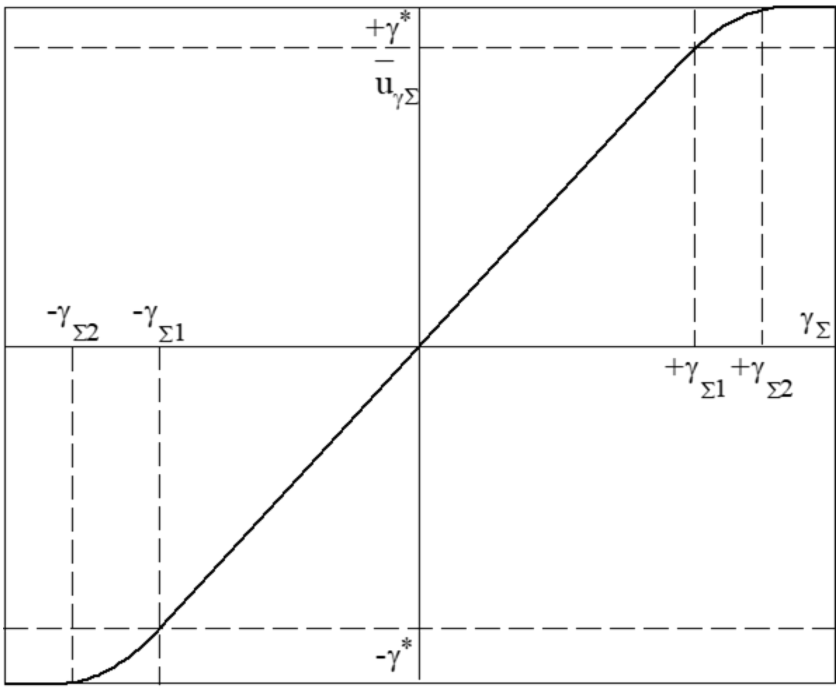

Fig. 3. Dependence of program signal with restrictions on aircraft roll angle

An example of simulation of high-frequency and low-frequency lateral motion cues is given in Fig. 4, in which the times t_1 and t_2 correspond to the beginning of the motion cueing.

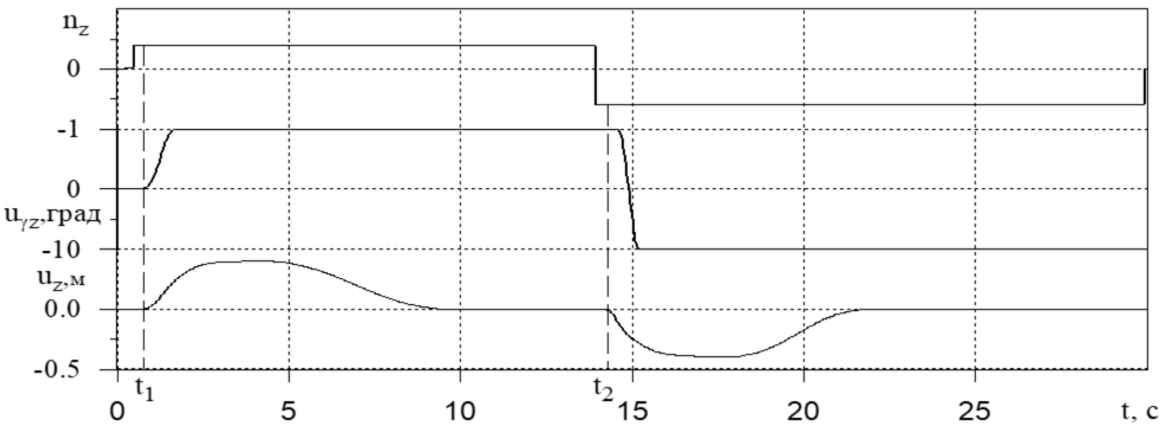

Fig. 4. Illustration of motion cueing caused by roll aircraft movement

Conclusion

This research introduces a practical solution for simulating low-frequency lateral motion in flight simulators used for training on non-maneuvering aircraft. By using a fourth-order low-pass filter along with integrated equations, it was found a way to better replicate both noticeable and subtle motion cues. This improvement aims to make the flight simulation more realistic for pilots and useful for those studying aerospace engineering.

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