PECULIARITIES OF MOTION CUEING FOR PRECISION CONTROL TASKS AND MANEUVERS

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Abstract

TsAGI's approach to simulation fidelity evaluation is presented, which assumes separate criteria for simulation fidelity assessment for precision control tasks and maneuvers.

The experimental data received in TsAGI on the effect of various drive algorithms on motion fidelity for various aircraft characteristics and different piloting tasks are presented. Analyzing and generalizing these and other data available, the main causes and mechanisms of drive algorithms effect are revealed. It has been shown that the acceleration simulation fidelity depends not only on drive algorithms parameters, but on piloting tasks and aircraft characteristics.

Criteria have been suggested and substantiated to approximately assess motion fidelity for various drive algorithms in various conditions simulated.

1 General Introduction

Even the most sophisticated flight simulators with large cockpit excursion the exact reproduction of aircraft specific forces and angular accelerations. Thus, there are two major problems in flight simulation: first, to determine the cockpit drive algorithms to ensure maximum adequacy of the simulated flight conditions to real ones for the given cockpit excursion limitations, and second, to evaluate agreement of the on-ground and in-flight results for the chosen algorithms. These both problems can be dealt with if we have motion fidelity criteria.

Whatever the drive algorithms are, the reduction of cockpit excursion as compared to this of aircraft movement is achieved at the expense of certain acceleration distortions introduced on ground. The effect of these distortions on simulation fidelity has not been sufficiently studied although there is quite a number of motion systems used and this particular effect has been considered in a number of publications. As it has been mentioned in many of these publications (see [1] for example), no reliable criteria to evaluate simulation fidelity for various drive algorithms have been developed so far.

Recently TsAGI developed an approach to assess simulation fidelity [2-4]. According to the approach developed at TsAGI, the simulation fidelity is evaluated by means of different criteria, according to: (1) the piloting task, (2) acceleration role in piloting, and (3) drive algorithms.

1. All piloting tasks can be divided into two types, namely, precision control tasks (disturbance or tracking) and maneuvers. In precision control tasks there are no large low-frequency accelerations; the main motion cueing method here is high-pass filtering, which leads to motion cues amplitude and phase distortions. These distortions are not directly perceived by the pilot, although they can affect aircraft handling qualities ratings and distort pilot training.

Considerable low-frequency accelerations are typical of maneuver-type tasks, such as turns, go-round, etc. While reproducing such accelerations on ground considerable false specific forces due to cockpit tilting and false cues opposite in sign to aircraft motion may arise. These false cues are easily perceived by a pilot; they can reduce simulation fidelity even greater than the absence of cockpit motion. Thus, different motion simulation fidelity criteria must be applied to precision control tasks and maneuvers.

2. The effect of drive algorithms on motion fidelity for precision tasks depends on the role of accelerations, namely, beneficial or negative. The effect of accelerations is defined as beneficial if the perceived cues facilitate controlling an aircraft. On the other hand, the effect of accelerations is defined as negative if the physiological effect of high-frequency accelerations is felt by the pilot as unpleasant. Negative acceleration effect is usually determined by the sustained high-frequency accelerations due to turbulence, or it may be caused by aircraft abrupt response to pilot activities at certain aircraft characteristics (small roll mode time constant, high values of short-period mode frequency, structural elasticity, etc.). The criteria to evaluate the role of accelerations in this or that case are given, for example, in [1,2,5]. Due to different motion cues roles in piloting, the assessment of motion simulation fidelity depends on motion cues role as well.

The criteria to evaluate motion fidelity for maneuver-type tasks are not subdivided according to the effect of accelerations. While maneuvering, aircraft motion is low-frequency, and the pilot operates in an open loop visually controlling aircraft motion parameters, thus specific forces and angular accelerations in this case do not play any considerable role; they are considered useful if reproduced without distortions.

3. Three main methods to reproduce motion cues are known: 1) high-pass filtering; 2) scaling; 3) cockpit tilting to imitate low-frequency lateral and longitudinal specific forces. The character of acceleration distortions, which each of the simulation methods create, is different: scaling decreases acceleration intensity equally at all frequencies without phase distortions; high-pass filtering cuts off low-frequency acceleration components, but creates noticeable phase distortions in high-frequency acceleration reproduced; cockpit tilting while reproducing low-frequency accelerations creates false sensations of angular motion. The effects of these distortions are independent: the effect of scaling does not depend on high-pass filter parameters and vice versa. That is why in TsAGI different motion fidelity criteria are used for different acceleration simulation methods.

TsAGI has performed quite a number of studies to develop motion fidelity criteria [2-4, others]. The present paper aims to dwell on the results and to summarize our experience in the field.

2 Motion Fidelity Criteria for the Precision Control Tasks

Motion fidelity criteria are considered here for simulation of roll accelerations and normal specific forces.

According to TsAGI's approach, different criteria are used to evaluate simulation fidelity in the case of beneficial and negative acceleration effects.

2.1 Beneficial Acceleration Effect

2.1.1 High-pass filtering

The criterion to evaluate the simulation fidelity for roll stabilization task is shown in fig.1. It is based on experimental data, received for different roll mode time constants, types of high-filters and their parameters (fig.2).

The criterion shows simulation fidelity as a function of filter break frequency ω_{br}, which is, for any type of high-pass filter, determined from the condition:

$$\left|Y_{hp}\left(j\omega_{br}\right)\right| = 0.7$$

Motion fidelity measures in this criterion are the relative values of piloting accuracy and pilot ratings (expressed as percentages):

$$\Delta\sigma_{\phi\,\text{relative}} = \frac{\sigma_{fixed} - \sigma_{motion}}{\sigma_{motion} - \sigma_{flight}},$$

$$\Delta PR_{\text{relative}} = \frac{PR_{fixed} - PR_{motion}}{PR_{motion} - PR_{flight}}$$

In fact, these measures show how piloting accuracy ($\Delta\sigma_{\phi\ \text{relative}}$) and pilot ratings ($\Delta PR_{\text{relative}}$) improve as compared to fixed-base case. On the other hand, they show to what extent the on-ground and in-flight data are different.

It follows from the criterion that roll accelerations are reproduced adequately if the filter break frequency is $\omega_{br} \leq 0.7$ sec^{-1}; if $\omega_{br} \geq 4$ sec^{-1}, simulation fidelity corresponds to fixed-base simulation; if $0.7 < \omega_{br} < 4 sec^{-1}$ simulation fidelity is medium. For the latter case the simulation fidelity degradation is proportionate to $\lg(\omega_{br})$.

The criterion to evaluate simulation fidelity for normal acceleration is shown in fig.1. In experiments, which formed the basis for the criterion, altitude control task was considered, since in this task the normal accelerations play a beneficial role (see [2,5]).

In the same way as the criterion for roll, the altitude control criterion is simulation fidelity measures as a function of high-pass filter break frequency. It is seen that high simulation fidelity for normal accelerations is achieved at break frequencies $\omega_{br} \leq 0.5$ sec^{-1}; it is medium within $0.5 < \omega_{br} < 2$ sec^{-1} ; at frequencies $\omega_{br} \geq 2$ sec^{-1} simulation fidelity as low as in the case of fixed-base cockpit.

2.1.2 Scaling

The criterion to evaluate the simulation fidelity for roll accelerations and normal specific forces for different scale gains is shown in fig.3.

It follows from the criteria that if accelerations and angular rates are scaling down, their simulation fidelity can be:

- high, if $\sigma_{nz\ simulator} > 0.02$ g, $\sigma_{p\ simulator} > 1$ *deg/sec*,
- medium, if $0.01 < \sigma_{nzsimulator} < 0.02g$, $0.5 < \sigma_{p\ simulator} < 1$ *deg/sec*,
- low, if $\sigma_{nzsimulator} < 0.01$ g, $\sigma_{p\ simulator} < 0.5$ *deg/sec*.

For the low-fidelity zone piloting accuracy remains the same as in fixed-base simulation, since the simulator accelerations and roll rates remain below pilot's sensitivity thresholds which are 0.5 *deg/sec* for roll rate perception and 0.01 g for normal acceleration perception.

As scaling gain increases, motion fidelity improves abruptly until its highest level corresponding to k=1. This is due to the fact that as the scaling gain increases, the motion cues exceed their threshold values and the amount of information received by the pilot through motion cues also increases.

When motion cues (roll rates and normal accelerations) exceed their threshold values more than 2 twice, no further scaling gain increase improves piloting accuracy and pilot ratings, and motion fidelity is the highest.

The combined effect of high-pass filtering and scaling on motion fidelity Q_Σ can be estimated as:

$$Q_\Sigma = Q(\omega_{br}) \cdot Q(k),$$

where $Q(\omega_{br})$ and $Q(k)$ can be determined from fig.1 and 3.

2.2 Negative Acceleration Effect

There are two cases when the effect of accelerations on piloting is negative: (1) when severe turbulence occurs, (2) when aircraft characteristics cause the abrupt response to pilot activities. If acceleration effect is negative, aircraft handling qualities depend not on piloting accuracy, which can be high, but the negative effect of high-frequency lateral accelerations. Thus, in case of negative acceleration effect, the main motion fidelity measure is pilot ratings.

2.2.1 High-pass filtering

The effect of high-pass filtering for cases where the effect of motion cues is negative is presented in fig.4. It can be seen that the influence of break frequency in this case is different to that for the beneficial effect. Motion fidelity starts to degrade quickly (pilot ratings improve) for break frequencies above 5 rad/sec, instead of 0.5-1 rad/sec for the beneficial effect.

Fig.4 shows that even if filter frequencies go up to 7-10 sec-1, high-pass filtering does not affect abrupt response simulation fidelity. This is due to the fact that the level of high-frequency specific forces does not change up to 7-10 sec^{-1} frequency values, since the main lateral acceleration spectrum power is about 7-10 sec^{-1} and over.

The data in fig.4 were received for roll stabilization task, τ_R=0.1 *sec*, the distance between the pilot location and rotational axis was h=1 m. At such roll mode time constant and pilot location, the aircraft response is abrupt.

2.2.2 Scaling

The effect of scaling on motion fidelity for roll and pitch control in case of negative acceleration effect can be estimated from the function in fig.5. Unlike the beneficial effect, scaling down here improves pilot ratings compared with real flight (motion fidelity degrades) due to the lower intensity of high-frequency specific forces. For values of simulator specific force equal to or less than their threshold values, motion fidelity is the same as for a fixed-base simulator.

It follows from the criterion that full scale high-frequency acceleration reproduction is necessary to adequately simulate abrupt response phenomenon.

As scaling gain decreases, simulation fidelity degrades (pilot ratings improve). At the scale gain k_{ny}=0.012/σ_{ny} in sway (roll control task) and k_{nz}=0.02/σ_{nz} in heave (pitch control task) lateral and normal specific forces approach their threshold values. As scale gain goes below these values, simulation fidelity becomes as low as on a fixed-base simulator.

3 Motion Fidelity Criteria for Maneuvers

Any maneuver-type task includes the tasks to precise control, thus the results of acceleration simulation shown in the previous chapters can be in many cases applied to maneuver-type tasks. But maneuvers may include large-amplitude tasks, and their simulation differs from simulation of precision-control tasks. The possible differences are considered in the present chapter.

3.1 Peculiarities of Acceleration Simulation for Maneuvers

According to TsAGI's approach, the criteria to evaluate motion fidelity for maneuver-type tasks are not subdivided according to the effect of accelerations. While maneuvering aircraft motion is low-frequency, and the pilot operates in an open loop visually controlling aircraft motion parameters, thus specific forces and angular accelerations in this case do not play any considerable role.

All acceleration distortions due to drive algorithms are usually divided into four types: 1) false lateral and longitudinal specific forces due to cockpit rotation in roll and pitch; 2) false motion cues opposite in direction to the aircraft motion cues ("opposite motion cues"); 3) amplitude acceleration distortions and 4) phase distortions. The effect of each of the mentioned types of distortions on simulation fidelity is different, and, thus, the criteria to estimate the effect of each type of distortions on simulation fidelity have to be different.

The peculiarities of acceleration reproduction for maneuvers are determined by the two first types of distortions, since the 3rd and 4th types of distortions (amplitude/phase distortions) do not affect maneuver simulation fidelity: while maneuvering a pilot is in an open control loop, and motion cues role is insignificant (the effect of phase/amplitude distortions is most pronounced in the case of precision-control task simulation).

The 1st and 2nd types of distortions, i.e. false specific forces due to cockpit rotation and motion cues opposite in sign, have been dwelled on in a number of publications (see [6], for example). The authors mentioned, that these types of distortions make simulation fidelity even lower than in the case of fixed-base simulation. Nevertheless, the effect of distortions in question has not been sufficiently studied even in kind.

The causes of false specific forces arising due to cockpit tilting are quite obvious. In flight the normal specific forces vector follows the aircraft motion in roll and pitch. As a result, no lateral or longitudinal accelerations arise while rolling or pitching in real flight. On a ground-based simulator this condition is not fulfilled due to the limitations in lateral and longitudinal cockpit displacements. That is why considerable false lateral specific forces arise in ground-based simulation.

The causes of opposite motion cues are more complex. Their effect depends not only on the type of high-pass filters (as it is commonly assumed), but (as our study shows) on the shape of the input signal as well.

Fig.6 shows high-pass filters responses to square-type signals. It should me mentioned that, while maneuvering, a square-type, not step-wise, input signal is more typical of angular rate and linear acceleration changes (in real flight, after the required angular rate or linear accelerations are attained, their input signals are later switched off). It can be seen that false motion cues opposite in sign, arising when linear accelerations and angular rates drop, greatly exceed the values of those false cues, which arise at the moment when linear accelerations and angular rates are created. Moreover, if the input is square, false motion cues arise even if the first order filter is used.

For simulation of precision-control tasks false opposite motion cues are less important. For that type of tasks angular rates and linear accelerations are continuous, reversible in sign and of high frequency (up to 3 sec^{-1} and even greater).

3.2 Normal Accelerations Simulation

The linear specific forces in LA tasks are, mostly, of square-type (fig.6). Thus, in reproduction of LA tasks we deal with opposite cues while simulating both the “front” and “rear” edge of specific forces. As our experiments show, the false cues arising during front edge simulation are either not perceived at all, or exceed pilot’s sensitivity thresholds inconsiderably.

The intensity of false cues at the rear edge exceeds their intensity at the front edge. That is why the effect of false opposite cues on maneuver simulation fidelity is generally determined by false cues arising at the rear edge of the reproduced accelerations.

As opposed to simulation of the front acceleration edge, the effect of false cues at the rear edge considerably depends on the duration of acceleration simulated. In the present paper criteria are discussed to estimate the effect of opposite false cues on maneuvers longer than 5 sec.

3.2.1 High-pass filtering

The data in fig.7 can be a criterion to estimate the effect of high-pass filtering on the false cues arising. It is pilot ratings as a function of the frequencies of the second order high-pass filters and for different short-period mode frequencies (similar data are received for the 3rd order high-pass filters). The scale to evaluate simulation fidelity is shown in fig.8.

The data received (fig.7) cover practically the whole ranges of normal accelerations (up to 0.3-0.4 g) and short-period mode frequencies of transport aircraft: ω_{sp} =1 sec^{-1} is typical of takeoff and landing modes; ω_{sp}=2 sec^{-1} characterizes high-velocity flight. The considered filters frequency range is typical of normal acceleration simulation. Thus the data in fig.7 can be used to evaluate acceleration simulation fidelity for maneuvers for different simulation conditions.

3.2.2 Scaling

If no washout filters are used, acceleration scaling affects only acceleration intensity; the scaling itself does not provoke any opposite false cues. If high-pass filtering and scaling are used simultaneously, this leads to both beneficial and false cues scaling down in the same proportion. Thus, if we simulate a maneuver with a given acceleration $n_{z\ given}$, scaling down k_{given} times leads to the same false cues sensations as in the case when the maneuver with $n_{z\ equivalent}=k_{given}n_{z\ given}$ is simulated at k=1.

3.3 Roll Accelerations Simulation

3.3.1 High-pass filtering

While modeling maneuvers in roll not only false motion cues of opposite sign, but also false lateral specific forces due to cockpit rotation arise. Their integrated effects are shown in fig.9. The data presented are functions of simulation fidelity ratings versus the second-order high-pass filters frequencies for various bank angles capture tasks for scaling gain k=1. The data in fig.9 are sufficient to evaluate roll simulation fidelity for different filters’ parameters, various aircraft characteristics and bank angles.

At low break frequencies the simulation fidelity worsening for roll maneuvers is mainly due to false lateral accelerations effect. As our experimental data show, at low break frequencies the cockpit tilt angles are almost equal to aircraft bank angles; at the same time false opposite roll rates are insignificant As the filter break frequencies increase, the tilt angles and, consequently, the false lateral accelerations decrease, but the false roll rates opposite in sign increase (at least up to ω_{hp}=1-2 sec^{-1}). Thus, as break frequencies increase, simulation fidelity starts to be determined by false roll rates opposite in sign. At the break frequencies about 1-2 sec^{-1} the false roll rates achieve their maximum, and simulation fidelity is the worst at these frequencies.

The points in fig.9 present our experimental data supporting the criterion. The bank angles in the experiments were up to 20^0, since for transport aircraft they do not exceed these values. False lateral accelerations arising in roll acceleration simulation were not compensated. We should mention that with the filter frequencies typical of simulators (about 1 sec^{-1}) it is impossible to compensate for such false accelerations since cockpit displacements are limited.

3.3.2 Scaling

It is obvious that acceleration scaling without filtering can not cause false angular rates opposite in sign. But if high-pass filtering is also used, scaling down leads to both false lateral accelerations and false angular opposite sign rates decrease. That is why roll simulation fidelity for the given bank angle ϕ_{given} , while *k*-time scaling down, is the same as roll simulation fidelity rating for the equivalent angle ϕ_{equiv} at which aircraft angular rates are *k*-times less than for ϕ_{given}. Aircraft roll rates in the first approximation are proportionate to bank angles, at least for angles up to 20^0. Thus, $\phi_{equiv}=k\cdot\phi_{given}$.

As a result, the integrated effect of filtering and scaling on roll simulation fidelity for the given bank angle ϕ_{given} can be estimated according to the equivalent bank angle ϕ_{equiv} from fig.9 for integrated effects of false opposite angular rates and false lateral accelerations.

3.4 Longitudinal Accelerations Simulation by Means of Cockpit Tilting

It is well known that longitudinal and lateral low-frequency accelerations can be reproduced by means of cockpit tilting. We consider here the simulation fidelity for longitudinal low-frequency accelerations arising during take-off running. Low-frequency acceleration component was reproduced by the second order low-pass filter.

The data in fig.10 demonstrate the effect of the filter frequency ω_{lp} on the perceived longitudinal acceleration fidelity. These and other data show that the principal constraints on using cockpit tilt in this way are due to false rotational sensations and false specific forces caused by jerky angular accelerations. In the area below the curves (fig.10) a pilot perceives cockpit tilting as linear accelerations. In the area above the curves, false sensations arise. To avoid these sensations the following criteria must be met: tilt velocity should not exceed approximately 2 deg/sec; false specific forces caused by angular accelerations should not exceed 0.01g.

It should be mentioned that we limit the rate of acceleration increase along with cockpit maximum tilt rate limitation. Thus, the frequency of the low-pass filter should be as high as possible, that is approaching the value which corresponds to the limits of cockpit angular rate and accelerations.

4 Conclusions

The approach proposed in TsAGI assumes that simulation fidelity is evaluated by means of different criteria, according to the piloting task, motion cues role in piloting, and drive algorithms used for the motion cues reproduction. The paper gives a description of the proposed criteria and recommendations to select drive algorithms parameters for different piloting tasks, aircraft characteristics and acceleration effects.

For precision-control tasks, the simulation fidelity can be evaluated as a function of high-pass break frequency and RMS of simulator specific forces and angular rates for any aircraft characteristics and drive algorithms.

For maneuver-types tasks, the main causes of simulation fidelity degradation are false motion cues of opposite sign arising due to high-pass filtering, as well as false specific forces due to cockpit tilting. The effects of these false cues on simulation fidelity depends on the high-pass filter characteristics, scale gain, aircraft bank angles and the acceleration values arising while maneuvering. The criteria described in the paper take into account all these parameters.

It is shown that the method to simulate low-frequency accelerations by means of cockpit tilting has serious limitations due to rotation sensations and jerky cockpit accelerations in sway and surge. To avoid these false sensations, the limitations on tilting rate and specific forces due to cockpit angular accelerations are determined.

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Copyright Statement

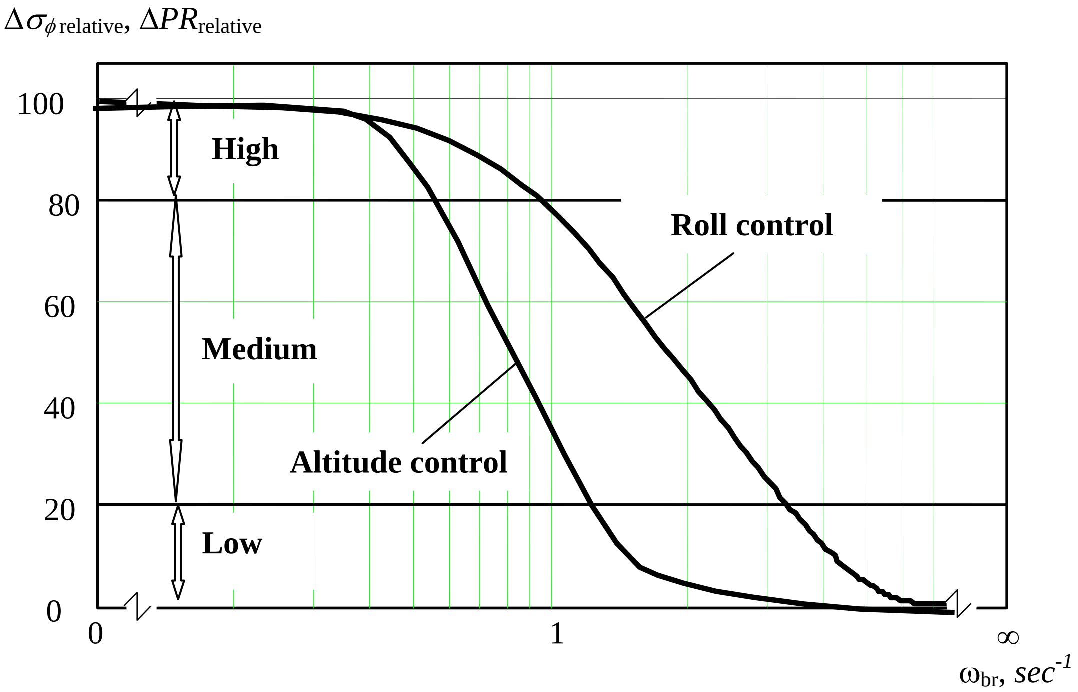

Fig.1. Motion fidelity as a function of high-pass filter break frequency for precision control tasks. Beneficial acceleration effect.

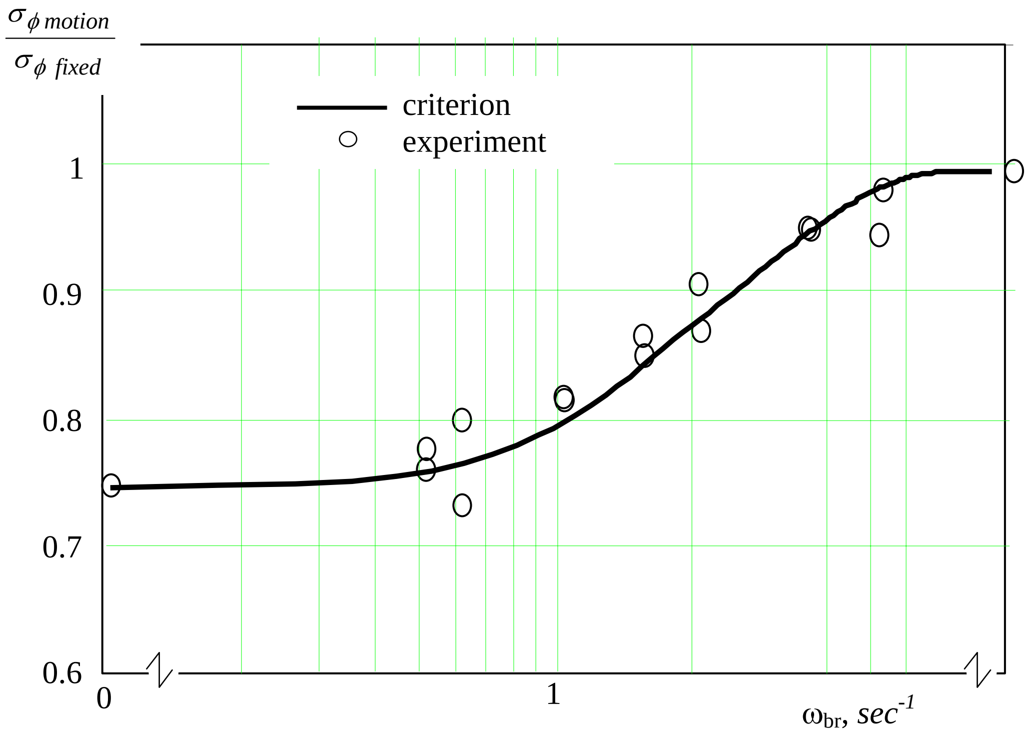

Fig.2. Example of the experimental data received on the criterion for high-pass filtering. Roll control task. Beneficial acceleration effect.

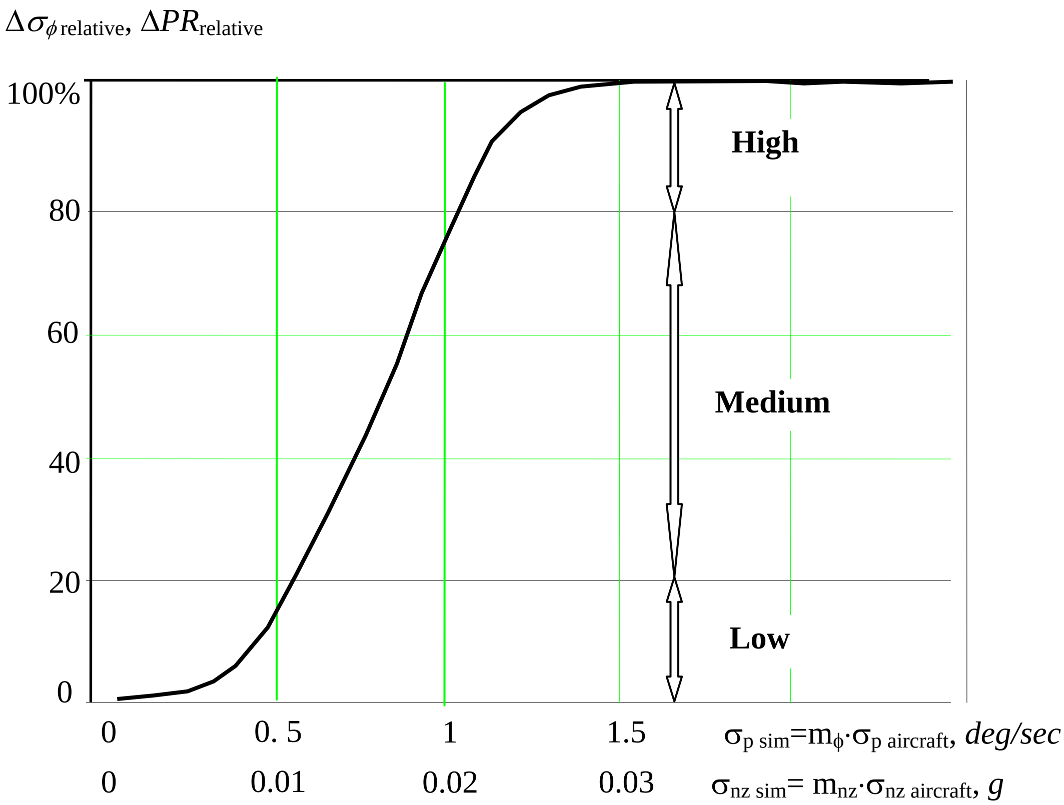

Fig.3. Motion fidelity as a function of simulator roll rate RMS and normal accelerations RMS.

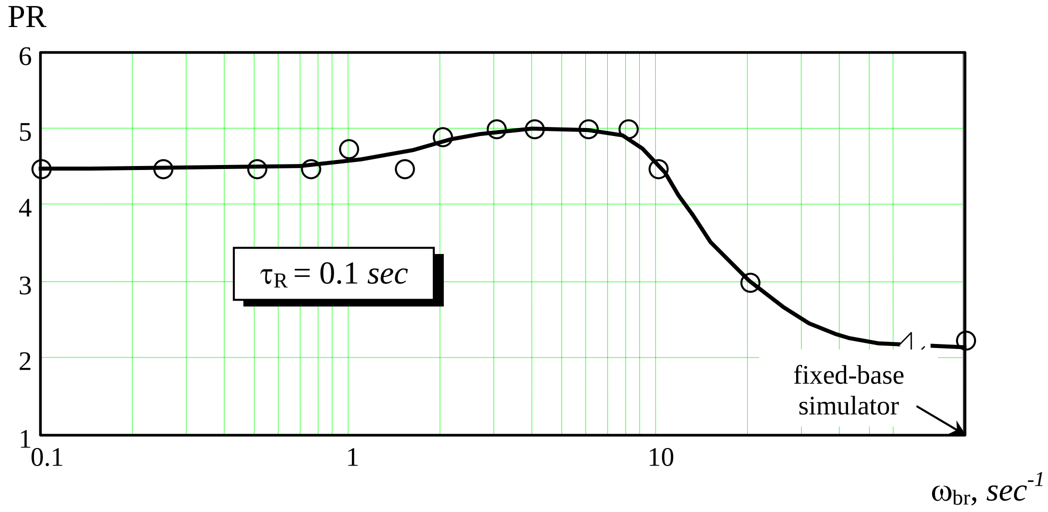

Fig.4. The influence of washout filter break frequency on motion fidelity for negative acceleration effect.

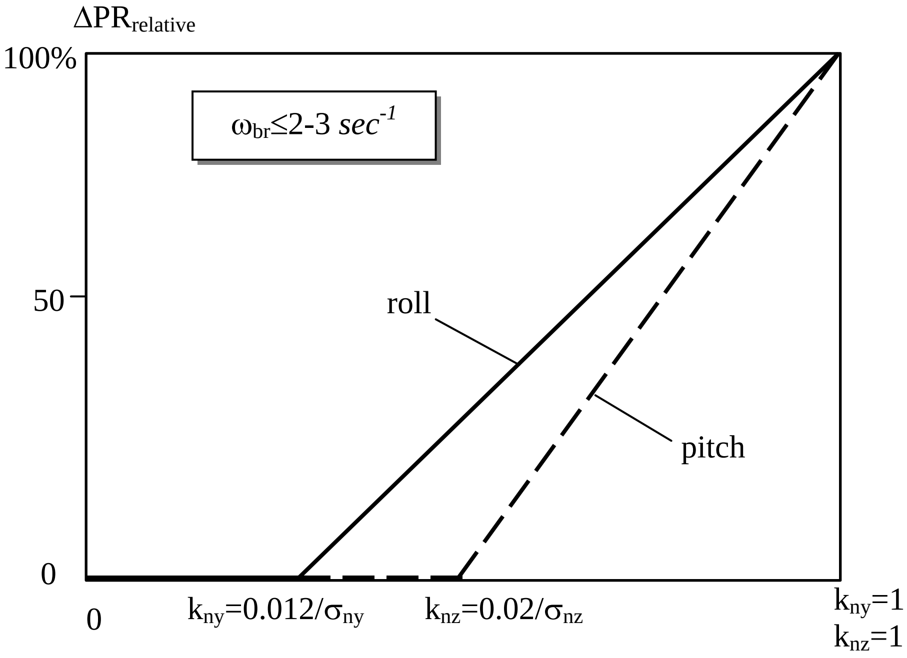

Fig.5. A criterion to estimate the influence of scaling for negative acceleration effect.

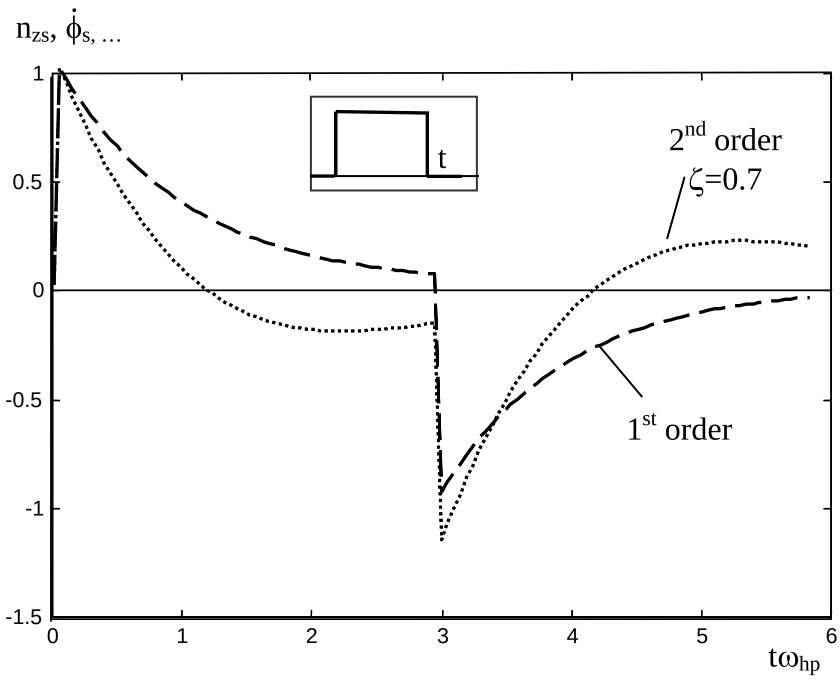

Fig.6. High-pass filters response to square-type input.

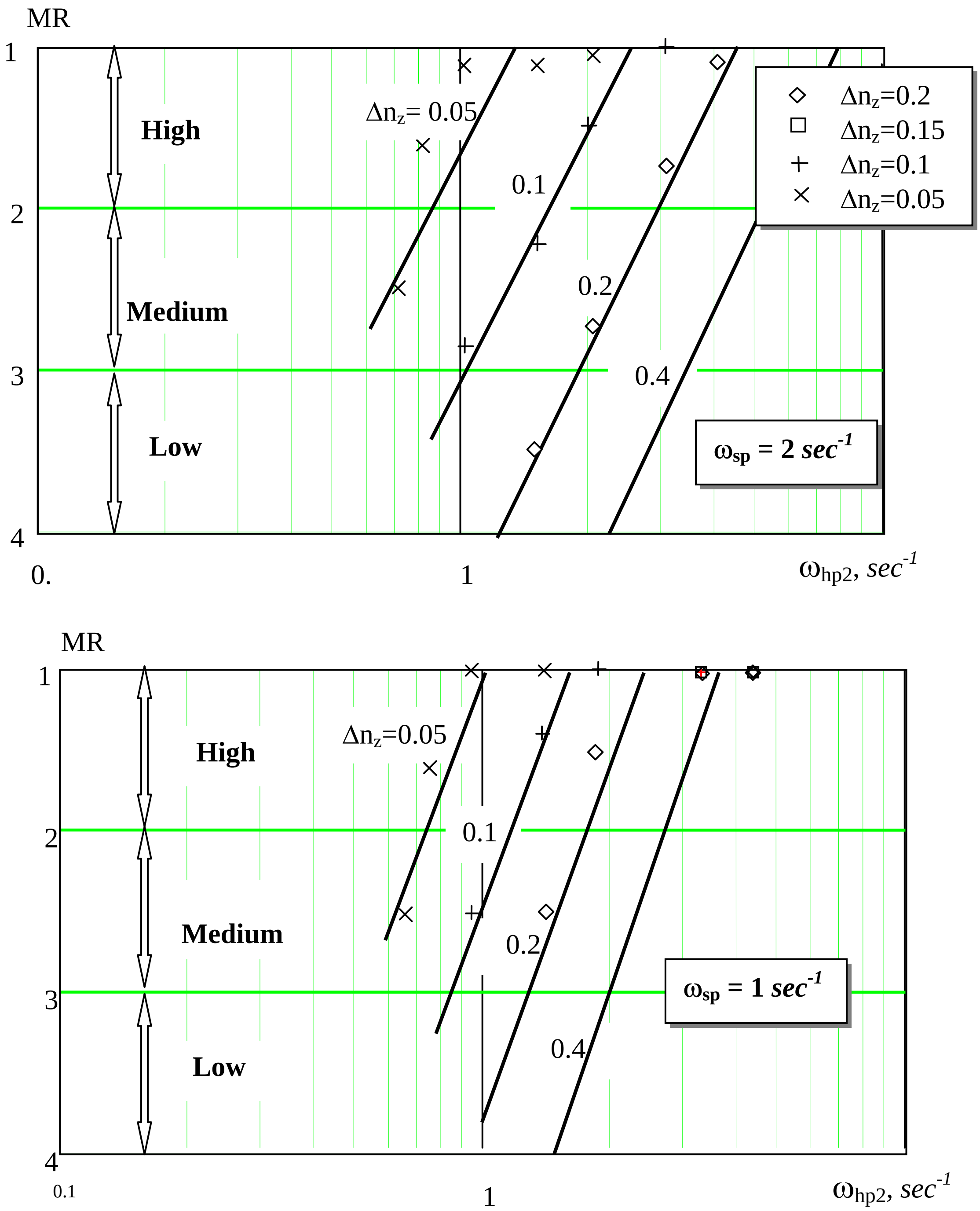

Fig.7. Simulation fidelity for rear edge of normal accelerations *vs* 2nd order filter frequencies, for different short-period mode frequencies.

Distortions in motion system	Aircraft motion	MR
Imperceptible	Non-distorted	1
Negligible	Non-distorted	2
Moderate	Distorted, but still distinguishable	3
Pronounced, unpleasant or jerky	Non-distinguishable on the background of distortions	4

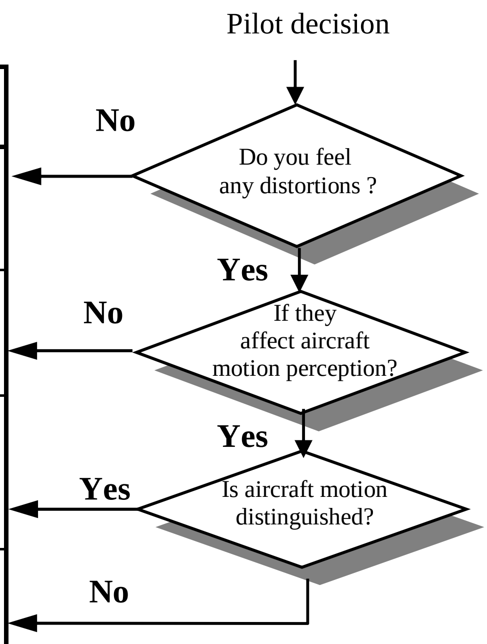

Fig.8. Motion Fidelity Scale.

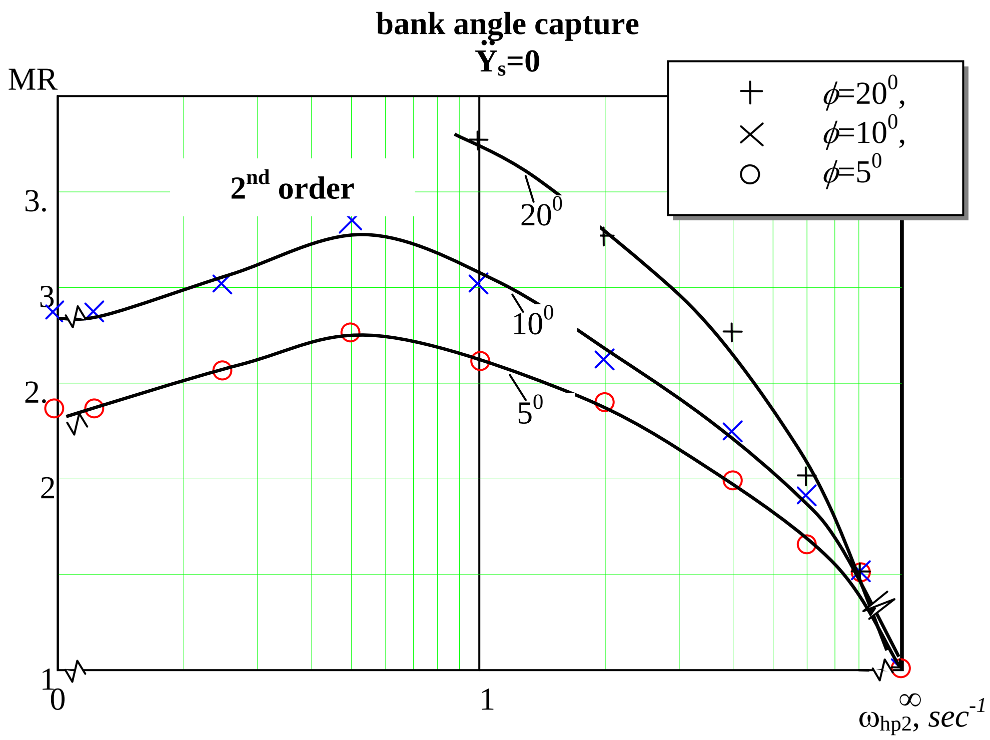

Fig.9. Integrated effects of false lateral accelerations and false opposite roll rates on motion fidelity ratings; the 2nd order high-pass filter.

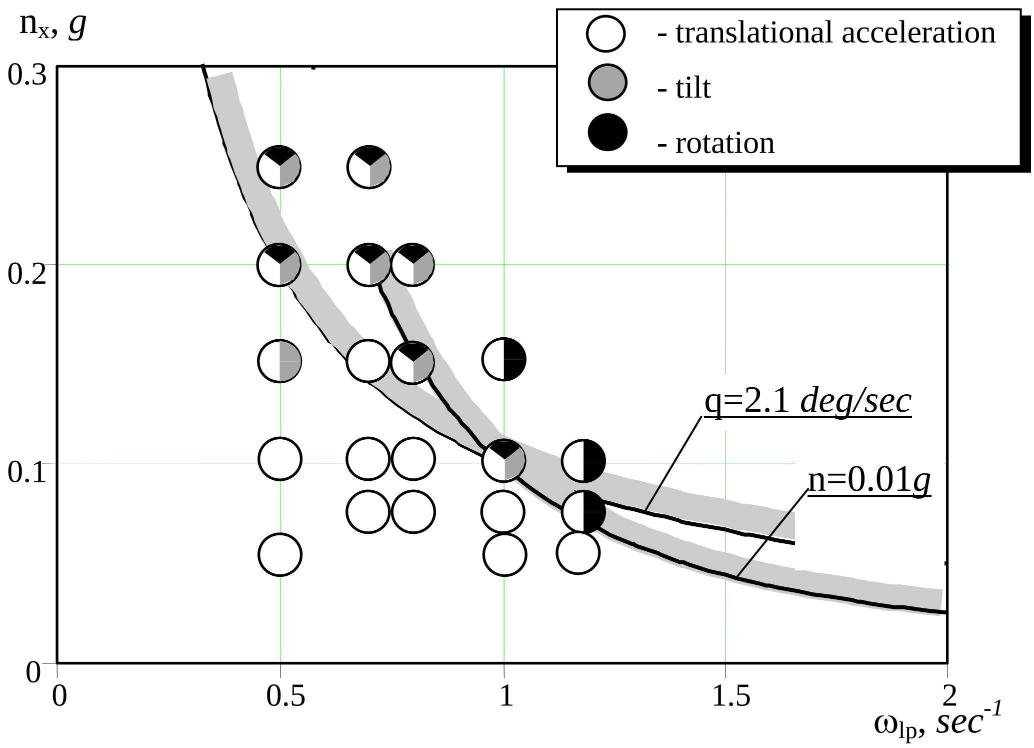

Fig.10. The boundaries of false sensations arising during low-frequency longitudinal accelerations simulation.