Peculiarities of Motion Cues Perception Against G-load

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Abstract
Presented are results of three experiments: differential thresholds along different translational DoF for different acceleration frequencies, the perception of over-threshold values of translational accelerations of different frequencies, sensitivity thresholds to angular motion under simultaneous G-load. It is shown that both the differential thresholds and the over-threshold acceleration perception are frequency-dependent; the regularity of this dependency is presented. On the basis of the on-ground and in-flight experiment, the angular motion sensitivity thresholds as a function of G-load are determined.

Introduction

The process of motion cues perception has always been the subject of great interest. The knowledge on the motion perception regularities is important for both theoretical (pilot perception models, the role of accelerations in piloting) and practical purposes (ground-based motion simulation fidelity, drive algorithms selection, requirements to simulator dynamic performance). Nevertheless, many problems of the motion cues perception are insufficiently studied so far.

One of the problems is the effect of considerable normal G-load on the perception of motion cues along other degrees of freedom. This problem is especially important to develop requirements to motion-on simulation of upset recovery maneuvers, which is the main task of European Collaborative Project SUPRA (Simulation of Upset Recovery in Aviation).

One of the most significant deficiencies of hexapod-type simulators, in terms of motion-on simulation of upset recovery maneuvers, is impossibility to reproduce considerable low-frequency G-loads which is typical of the maneuver. But along with G-load, the other motion cues arise while upset recovering, which are possible to be reproduced on hexapod-type simulators. Thus, the question arises: how strong is effect of considerable G-loads on the perception of motion cues along other degrees of freedom (DoF), or in other words, do we need to reproduce motion cues along other DoF if we can not reproduce considerable G-loads? The lack of sufficient data on this question was, seemingly, the reason for the available guidance to train flight crews for upset recovering [1] does not give any requirements for motion-on simulation. As a result, flight crews are trained at present on fixed-based simulators or on simulators with motion system switched-off. Nevertheless, it is known that the lack of accelerations or their inadequate reproduction on ground-based simulators may be one of the main sources of simulation and training errors.

At present, the most sufficient data on the effect of normal g-load on motion cues perception can be found in [2,3,4]. These works present, in particular, differential thresholds of sensitivity to accelerations for the three linear degrees of freedom, and the law of over-threshold acceleration perception. But the acceleration frequency range considered in the works was rather narrow (about 4 rad/sec). Frequencies of linear accelerations arising during upset recovery maneuver vary in a much wider range, low frequencies (below 1 rad/sec) included. Thus, one of the goals of the present paper is to study the effect of acceleration frequency on differential thresholds and on the regularities of perception of over-threshold acceleration values.

In [2,4] it was shown that normal G-load affects angular motion perception considerably. The values of G-load considered in the ground-based experiments did not exceed 1.05-1.08 g. In reality, G-load values while upset recovering can approach 1.5-2.0g and even more. Due to travel limitations, it is impossible to reproduce such G-loads on simulators of hexapod type. Thus, the second goal of the present paper is to conduct in-flight experiments to determine the effect of high G-load on angular motion sensitivity thresholds for greater range of normal accelerations value and greater range of linear and angular motion frequencies.

1. Experimental Procedure

Three experiments were conducted:
1) to determine the effect of frequency on the differential thresholds,
2) to determine the effect of acceleration frequency on the perception of over-threshold acceleration values,
3) to determine angular motion sensitivity thresholds (roll, pitch, yaw) for different values of normal g-load and for different frequencies of angular rate and normal accelerations;
The first two experiments were conducted on TsAGI PSPK-102 flight simulator, the third experiment was conducted both on PSPK-102 flight simulator (figure 1) and in-flight simulator Tupolev-154 of Flight Research Institute, Russia, (figure 2).

<u>Experiment 1.</u>

The profile of linear accelerations corresponds to the following equation:

$$n_{total} = n + \Delta n ,$$

where

$$\begin{aligned} n &= A_0 \sin \omega_0 t \\ \Delta n &= \left(a \cdot t \cdot A_0 \sin \omega_0 t\right) \sin \omega t \end{aligned} . \qquad \textbf{(1)}$$

In (1) *n* is a “background” accelerations, Δn is an “imposed” accelerations.
The selection of the amplitudes and frequencies of the background and imposed accelerations was conducted to meet the requirements to stay within the simulator travel limitations.
Frequency of the “background” acceleration ω_0 was equal 1 *rad/sec* in all cases; frequencies of the “imposed” acceleration ω were 2.5 and 12.56 *rad/sec*; amplitudes of the “background” acceleration A_0 varied from 0.01 to 0.1 g.
For each amplitude of the “background” acceleration the amplitude of the “imposed” acceleration (1) increases slowly (a=0.001-0.01 sec^{-1}, depending on the imposed signal frequency) until the subject starts to feel it.
Three participants took part in the experiment. Subjects’ task was to indicate the moment of the sensation beginning by deflecting the stick according to the direction of motion and with the frequency of the motion for frequency 2.5 rad/sec; for frequency 12.56 rad/sec the beginning of the sensation was indicated by simple stick deflection.
Due to PSPK-102 inherent distortions, the acceleration reproduced differed from one calculated according to (1). Thus, the output acceleration distortion signal was analyzed instead of input; for each degree of freedom it was measured with an acceleration transducer.
The threshold values received for each subject were averaged; their scattering is defined by root-mean-square (RMS). To evaluate the measurement accuracy we assume the transducer error in measuring accelerations is 0.001 g, the relative error in determining the measured acceleration is 5%. We assume also that the measurement errors and scattering in threshold values estimated by a subject are independent. Thus, RMS of thresholds for each subject is determined from the following expression:

$$\sigma = \sqrt{\left(\frac{\sum_{j=1}^{n} \left(x_j - m\right)^2}{n-1} + \left(0.05m\right)^2 + \left(0.001\right)^2 \right)} ,$$

where x_j - the value of sensitivity threshold for *j*-th run, n - the number of runs, m - the mean value of thresholds.

Experiment 2.

The profile of linear accelerations corresponds to the following equation:

$$n_{total} = n + \Delta n \ ,$$

where

$$\begin{aligned} n &= A_0 \sin \omega_0 t \\ \Delta n &= (\Delta A \sin \omega_0 t) \sin \omega t \end{aligned} \ . \qquad \textbf{(2)}$$

In (2) n is a “background” accelerations, Δn is an “imposed” accelerations.
The selection of the amplitudes and frequencies of the background and imposed accelerations was conducted to meet the requirements to stay within the simulator travel limitations.
Frequency of the “background” acceleration ω_0 was equal 1 *rad/sec* and did not vary in experiment; frequencies of the “imposed” acceleration ω were 2.5 and 12.56 *rad/sec*; amplitudes of the “background” acceleration A_0 varied from 0.01 to 0.1 g; amplitudes of the “imposed” accelerations ΔA (2) varied discretely from run to run; from 4 to 6 values of ΔA were considered for each value of A_0.
For each amplitude of the “background” acceleration the amplitude of the “imposed” acceleration ΔA varied discretely from run to run providing the acceleration intensity variation.
As in Experiment 1, the reproduced accelerations were analyzed (the values registered by transducers).
Two participants took part in the experiment. Subjects’ task was to estimate the intensity of the imposed accelerations according to the special scale (figure 3). The ratings received in several tests were averaged.

Experiment 3.

1. On-ground experiment.
TsAGI PSPK-102 6DoF Flight Simulator was used for this study.
In experiment, angular rate sensitivity thresholds (roll, pitch, yaw) were determined on the background of the simultaneous normal g-load. The motion of the cabin both in heave and roll (or pitch, yaw) was sinusoidal:

$$Z_s(t) = \frac{A_0}{\omega_z^2} \sin \omega_z t \ \text{ - in heave}$$

$$\varphi_s(t) = \frac{K \cdot t}{\omega^2} \sin \omega t \ \text{ - in roll (pitch, yaw)}$$

The selection of the amplitudes and frequencies of the “background” normal accelerations and “imposed” angular motion was made to meet the requirements to stay within the simulator travel limitations and to prevent false cues from cabin tilt.
The amplitude A_0 of the normal accelerations varied discretely from test to test, its values varied from 0.05 to 0.1 depending on DoF and frequency of angular and linear motion.
In every test the amplitude of angular motion Kt increased slowly (K= 0.069 deg/sec^3) until a subject was able to distinguish the direction of angular motion.
To determine the effect of frequencies, experiment was conducted for different frequencies of angular motion and normal accelerations:

1) ω_z = 1 rad/s, ω = 4 rad/s;
2) ω_z = 4 rad/s, ω = 1 rad/s.

Two test pilots and one human-operator participated in the experiment. Subjects’ task was to indicate the moment of the angular motion sensation beginning by deflecting the stick according to the direction of motion and with the frequency of the motion.
The threshold values received for each subject were averaged; their scattering is defined by root-mean-square (RMS). RMS of thresholds for each subject is determined from the following expression:

$$\sigma = \sqrt{\frac{\sum_{j=1}^{n} (x_j - m)^2}{n-1}} \ ,$$

where x_j - the value of sensitivity threshold for j - th run, n - the number of runs, m - the mean value of thresholds.

2. In-flight experiment.
In-flight experiment was conducted at attitude 5000 m and velocity 450 km/h.
The angular motion thresholds were determined for the sinusoidal roll motion with frequency about 0.5 rad/s and amplitude slowly increasing until the subject pilot starts to feel the roll motion. The roll motion was imposed on the sinusoidal G-load with frequency about 0.2 rad/s and different amplitudes: Δn_z=-0.2; Δn_z=0; Δn_z=0.4; Δn_z=0.6.
The task of the subject pilot was to indicate the beginning of the angular motion sensations by pushing a knob "phenomenon indicator". The angular threshold was determined according to the indicator. To receive sufficient statistics every test was repeated several times.
The task of the first pilot was to support the sinusoidal roll motion. To provide Δn_z=0 the pilot performed a level flight; to provide Δn_z=0.4 and Δn_z=0.6 he performed turns; to provide Δn_z=-0.2 he performed a "zoom" maneuver.
The following flight parameters were registered: normal G-load, bank angle, roll rate, wheel deflections, phenomenon indicator, flight attitude and velocity.
The procedure of the in-flight experiment was preliminary tested in on-ground simulator PSPK-102 TsAGI.

2. Analysis of the Results

2.1 Differential thresholds for different acceleration frequencies

In physiology, differential threshold means minimum increment in stimulus intensity determined against this stimulus background non-zero value. It is expressed as value ΔJ or is referred to the background stimulus intensity $k= \Delta J/J$.
The knowledge on differential thresholds is indispensable, for example, to assess acceptable levels of roughness when reproducing both specific forces and angular accelerations [3,6,7], or the necessity of reproduction high-frequency specific forces under simultaneous G-loads.
In [3] the differential thresholds were determined for linear degrees of freedom only. The fact is that, on the one hand, maintaining a certain level of constant or low-frequency linear accelerations is characteristic of piloting in general. On the other hand, maintaining a certain constant non-zero angular acceleration, or velocity value at least, hardly ever occurs while piloting. For these and some other reasons the data on differential thresholds are more valuable for linear degrees of freedom for practical purposes.
In previous research [2], differential thresholds were received for sinusoidal accelerations of a single frequency (4 rad/s). Here, we present experimental results received for another acceleration frequencies. Both experimental data and estimations are given in Figures 7,8. Experimental data is shown in circles, estimations are shown in lines.
The data received earlier [2] shows that within a certain range of acceleration values the differential thresholds of acceleration perception conform to Weber's law and can be found as:

$$J = n_0 + k \cdot {}^{\Delta n}\!/_{n}, \qquad \textbf{(3)}$$

where n_0 is the absolute acceleration perception threshold, coefficient k depends on DoF.
It is known that absolute thresholds of linear acceleration perception depends on acceleration frequency [2]. This fact as well as the data received in the course of the experiment gave us the basis to suppose that, for the differential thresholds, it is coefficient $k(\omega)$ in (3) which should be dependent on acceleration frequency, i.e.

$$J = n_0(\omega) + k(\omega) \cdot {}^{\Delta n}\!/_{n}, \qquad \textbf{(4)}$$

where $n_0(\omega)$ is the absolute threshold value of the acceleration at the particular frequency.
The function $k(\omega)$ is similar to that which describes the absolute thresholds as a function of acceleration frequency [2]. Figure 4 shows coefficient k as a function of frequency for the three linear accelerations.
As it is seen from figure 5, the estimations according to (4) are in a good agreement with the experimental data received in present and other works. The good agreement of the data proves the conclusion that differential thresholds are frequency-dependent.
The only disagreement between the estimations and experimental data is observed for lateral and longitudinal accelerations of high frequencies (12.56 rad/sec), which can be explained by the fact that for high intensity stimuli of

any kind Weber-Fechner law does not hold. The data received by the authors show that if acceleration frequencies are over 12.56 rad/s, Weber-Fechner law is broken as longitudinal or lateral specific forces exceed 0.04-0.05*g*.

2.2 Perception of over-threshold linear accelerations of different frequencies

It was suggested in the 19th century that the function of sensations' intensity *R* of stimulus' value follows the Weber-Fechner law:

$$R = K \cdot \log(S)\ . \qquad \textbf{(5)}$$

In [2] authors collected data on the perception of over-threshold values of accelerations when they analyzed the permissible levels of non-linear distortions, which arise while reproducing linear or angular accelerations. For this study a special scale was developed (see figure 3) to assess the intensity of the distortions: *MR*=1 being the highest fidelity, when the distortions are not felt by a pilot, and *MR*=4 being the lowest fidelity, when the intensity of the jerks prevents aircraft motion being distinguished due to the distortions.
It was shown, in particular, that for medium intensity specific forces their simulation fidelity depends not on absolute (Δn) but on relative ($\Delta n/n$) distortions, and for acceleration values $n \geq 0.015$g, the relationship between motion fidelity ratings *MR* and acceleration noise values (distortions) can be described by the following expression derived from Weber-Fechner formula (5):

$$MR = K \cdot \log(1 + {\Delta n_z}/{n_z}) + 1\ . \qquad \textbf{(6)}$$

The distortion frequency range considered in [2] was limited with high frequencies (from 2 to 6 Hz). The data received in the present experiments (figure 6) allow us to extend this law over accelerations with lower frequency spectrum of the "imposed" accelerations.
This can be done by introducing coefficient $k_1(\omega)$ (figure 7), which depends on acceleration frequency:

$$MR = K \cdot \log(1 + k_l(\omega)\, {\Delta n_z}/{n_z}) + 1\ . \qquad \textbf{(7)}$$

Values of *K* depend on the degree of freedom. For the vertical axis, function (7) can be presented as follows:

$$MR = 8.0 \cdot \log(1 + k_l(\omega)\, {\Delta n}/{n}) + 1\ .$$

We suppose that the physics for function $k_1(\omega)$ is the same as for $k(\omega)$ for differential thresholds. Function $k_1(\omega)$ was adjusted to meet the condition of a good agreement between the estimations and experimental data (figure 6).

2.3 Angular motion perception under simultaneous G-load

Understanding of G-load effect on angular motion perception is indispensable for motion cueing since in real flight specific forces and angular accelerations act simultaneously. For practical purposes, normal acceleration effect is the most important.
It is known that large low-frequency normal accelerations are impossible to be reproduced on hexapod-type simulators. The knowledge of their effect on angular motion perception can allow estimation of the necessity to reproduce the angular motion under large G-loads.
The problem was studied by authors in [2]. On a ground-based simulator the effect of normal accelerations on angular motion perception is possible to study only if accelerations are of small amplitude and high frequencies (over 1 rad/s). That is why, to analyze the effect of low-frequency normal accelerations, we use in-flight data received within SUPRA project and the in-flight data received earlier in the course of joint TsAGI-FRI study (a part of the study is described in [4]).
Simulator data. The data received in the present work cover greater range of G-loads then that considered in [2]. Figure 8 show the integrated simulator data for roll and pitch.
It is seen that the effect of normal g-load on angular motion thresholds is similar for all the three angular DoF: as normal g-load increases from 0 to a certain value (in our case, 0.03-0.05g), angular motion thresholds increase considerably; further increasing of normal g-load leads to much smaller increasing of the thresholds.

The effect of normal accelerations on angular thresholds can be described by the following function:

$$p = p_0 + k_1 A_{n_z}, \ \text{if } A_{n_z} \le 0.04g$$
$$p = (p_0 + 0.8) + k_2 A_{n_z}, \ \text{if } A_{n_z} > 0.04g \quad , \qquad \textbf{(8)}$$

where p_0 is the absolute threshold value of the angular motion, A_{nz} is the increment of normal acceleration relative to n_z =1.
Coefficients k_1 and k_2 in (8) can be assumed the same for roll, pitch and yaw: k_1=20, k_2=1.5.
We suppose that the complexity of function (8) can be accounted for by peculiarities of perception of over-threshold values of normal accelerations (at least, for the sinusoidal accelerations).
The data shown in figure 8 are received for different frequencies of normal accelerations and angular motion. Besides, the data corresponding to the first range of normal accelerations variation (below 0.04g) practically coincide with the data received in [5] for the random normal accelerations. Thus, we may conclude that coefficients k_1 and k_2 in (8) does not depend on frequency spectrum of specific forces and angular accelerations.
In-flight data. Figure 9 presents data received within SUPRA project and those received earlier in [4].
The data in figure 9 show that low-frequency (about 0.2-0.5 *rad/sec*) normal accelerations dull the sensitivity to angular motion: as g-loads increase from 0 to 0.5*g*, the angular sensitivity threshold values increase linearly by about 50%.
According to in-flight data, the effect of normal accelerations on angular motion thresholds has no breaks and can be described as follows:

$$p = p_0 + k_2 A_{n_z} , \qquad \textbf{(9)}$$

where p_0 – the absolute sensitivity threshold of the angular motion (received in flight).
In the in-flight experiments conducted here and in [4] (figure 9), different frequencies of normal accelerations and angular motion were considered: ω_{nz} = 0.5 rad/s, $\omega_{p,q}$ = 2 rad/s [2]; ω_{nz} = 0.2 rad/s, $\omega_{p,q}$ = 0.5 rad/s. Nevertheless, functions $p(A_{nz})$ received in the experiments have similar slope regardless of the frequencies of angular motion and normal acceleration, i.e. k_2=const. A good agreement between the estimations and experimental data allows us to assume k_2 in (9) to be equal to k_2 in (8), i.e. k_2=1.5. It means that the function, received on on-ground simulator for high-frequency g-loads over 0.04g, coincides with the function for low-frequency g-load received in flight.
Analysis of the in-flight data shows that the frequency of the angular motion affect the value of absolute threshold p_0 in (9). This effect results in shifting function (9) along vertical axis.
The analysis and experimental data allow us to make the following conclusions:
1. To estimate the effect of normal accelerations greater than 0.04g, function (9) or the second equation in function (8).
2. To estimate the effect of small values of normal high-frequency accelerations (frequencies higher than 1 rad/s, values smaller than 0.04g), first equation in function (8) can be used.

Conclusions

1. Differential thresholds as well as the perception of over-threshold values of acceleration are functions of acceleration frequency. The dependency can be taken into account by weight coefficients which depend on acceleration frequency.
2. Angular motion perception thresholds depend on G-load level. The functions of angular motion thresholds *vs* G-load received in flight and on ground coincide for G-load greater than 0.04g. The function's slope does not depend on frequencies of G-load and angular motion; the frequency of the angular motion affects only the value of the absolute threshold p_0 in the function.

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Figures

Figure 1: TsAGI PSPK-102 flight simulator

Figure 2: FRI Tupolev-154 in-flight simulator

Aircraft motion	MR
Non-distorted	1
Negligible	2
Distorted, but still distinguishable	3
Non-distinguishable on the background of disturbances	4

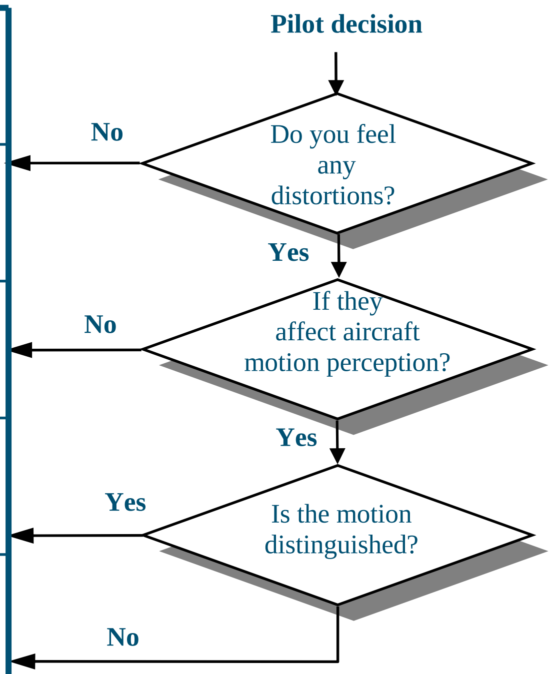


Figure 3: The scale used in Experiment 2

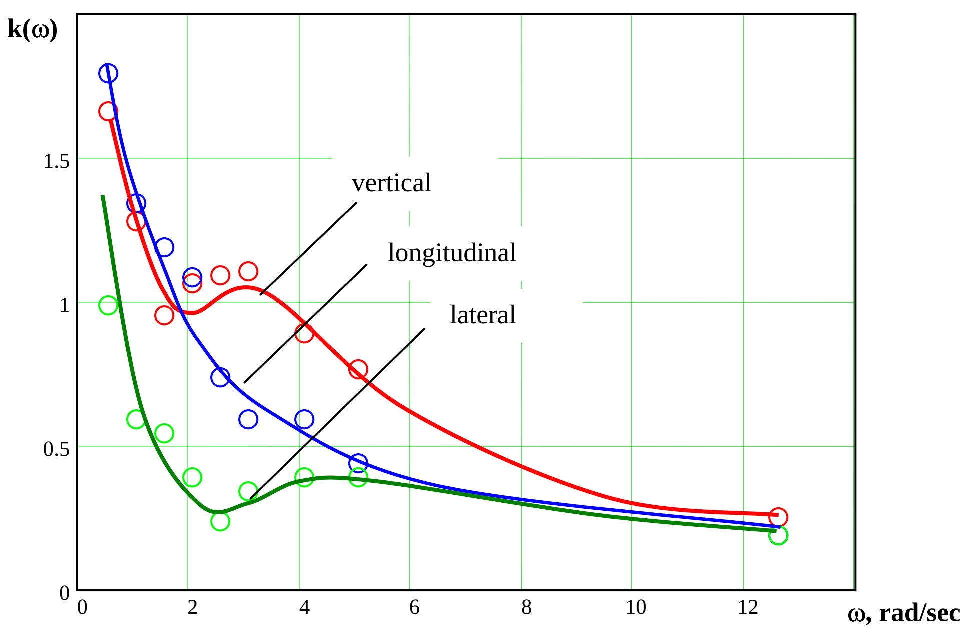


Figure 4: Coefficient $k(\omega)$ as a function of acceleration frequency

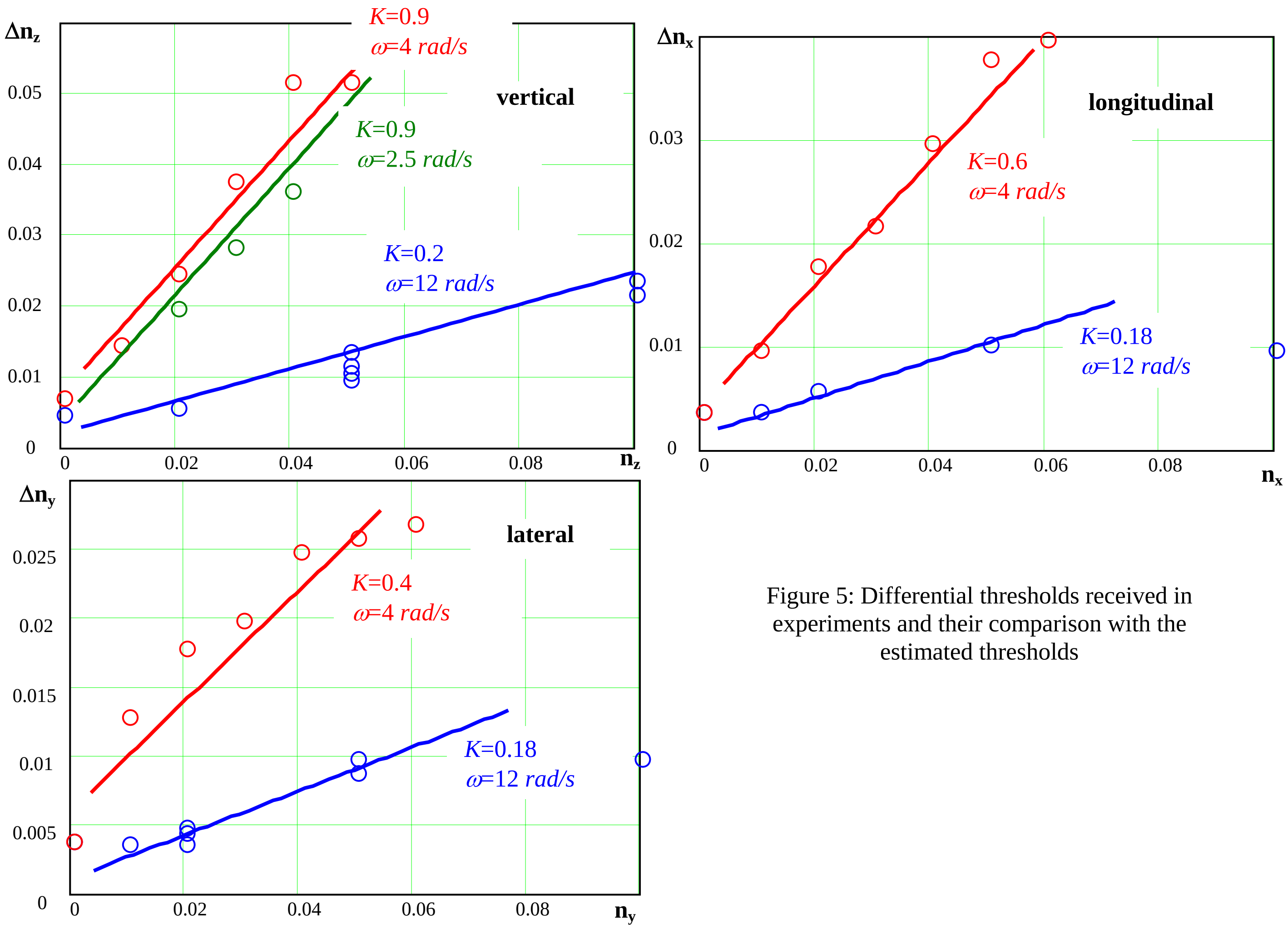


Figure 5: Differential thresholds received in experiments and their comparison with the estimated thresholds

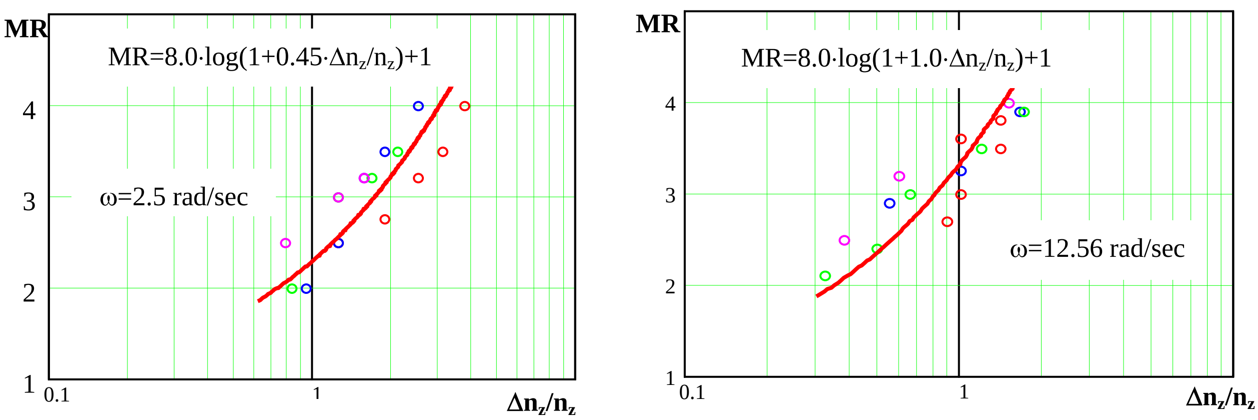


Figure 6: The perception of over-threshold normal accelerations of different frequencies. Comparison of estimations according to (8) and experimental data

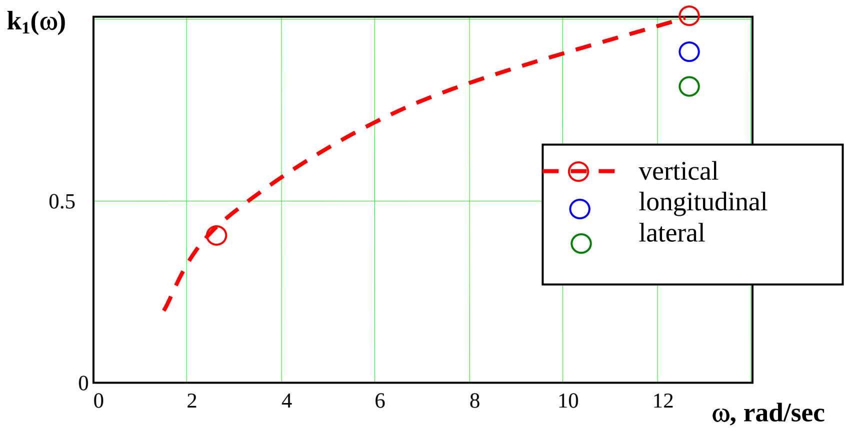


Figure 7: Coefficient $k_1(\omega)$ as a function of acceleration frequency

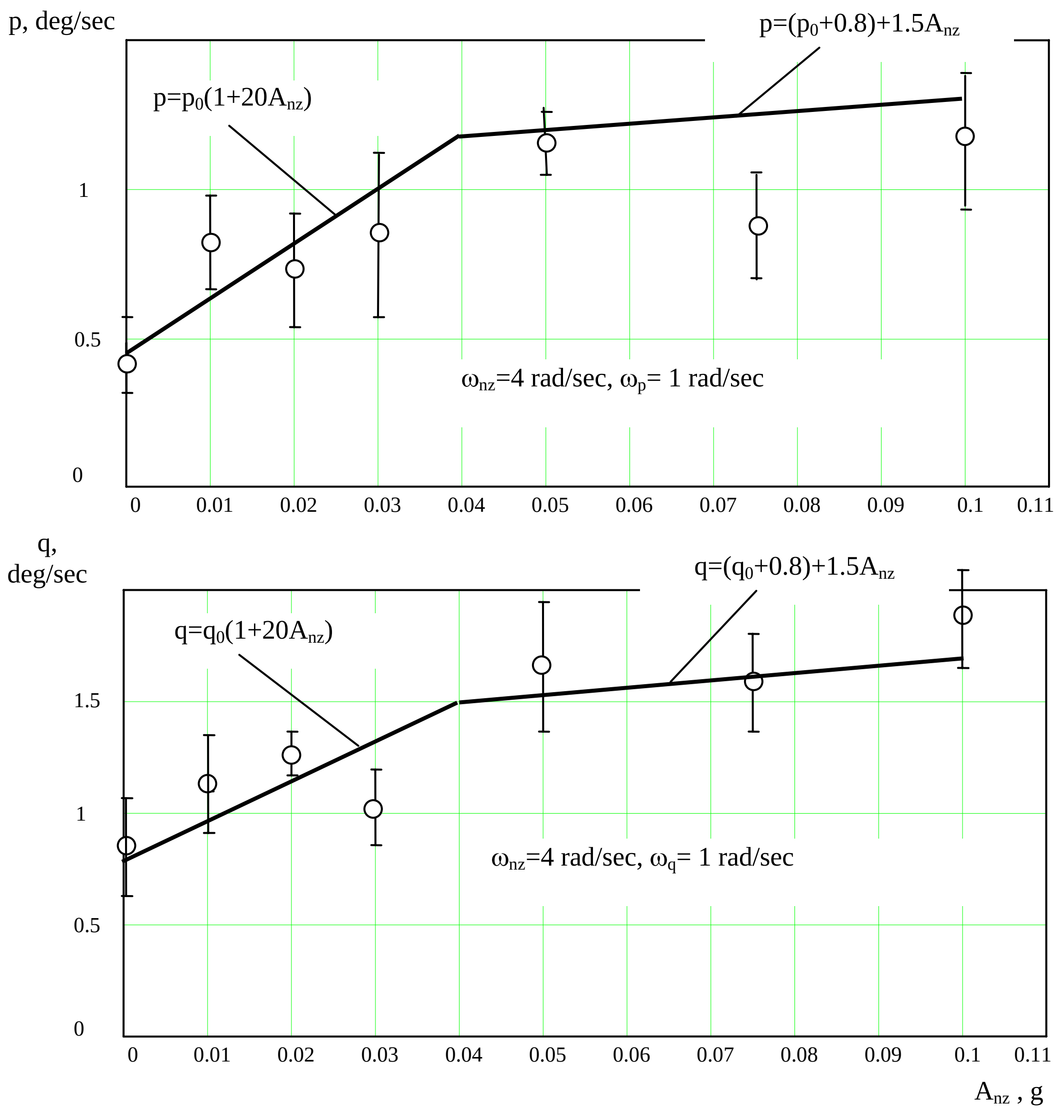
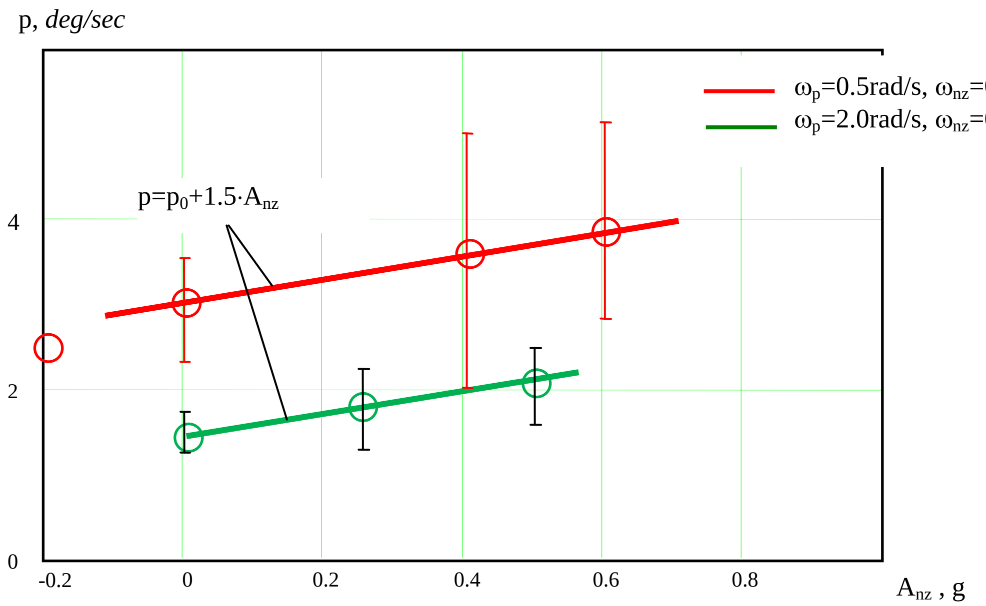


Figure 8: Roll and pitch simulator data



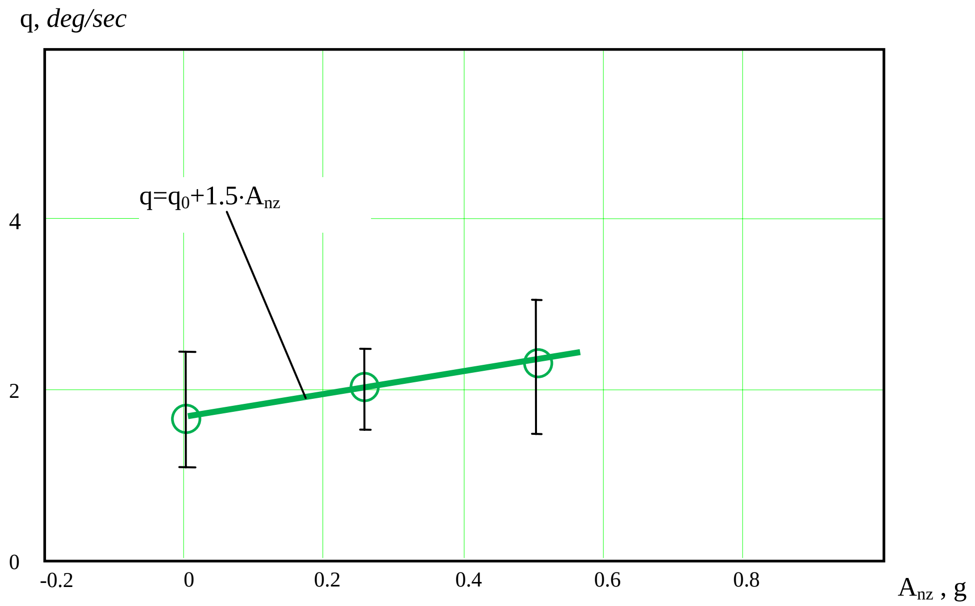


Figure 9: In-flight data, received within SUPRA and in [4]