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REFINEMENT OF THE MODEL OF PILOT PERCEPTION OF AIRCRAFT MOTION IN UPSET CONDITIONS UTILIZING FLIGHT TESTS RESULTS

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Abstract

Presented in the paper are the results of research carried out in the Gromov flight Research Institute (GFRI). In-flight experiments are conducted on Ilushin-103 aircraft to determine pilot sensitivity thresholds to angular and linear motion in order to clarify and complete the database available. Special attention is paid to the effect of normal G-load on the angular motion perception. The paper describes experimental procedure which is the factor determining effectiveness and completeness of the in-flight results. The results received confirmed and broaden out the data on the sensitivity thresholds, in particular on the effect of normal accelerations on the perception of aircraft angular motion.

1 Introduction

Both national, and foreign experience of investigation of aviation incidents shows, that rather big number of civil aircraft accidents is related to upset positions occurrence (for the different reasons) and the subsequent wrong actions of crew. The subsequent analysis of such accidents revealed that pilot didn’t understand or didn’t feel the tendencies of flight situation development preceding entering into upset conditions. One of the possible reasons of such aircrew behavior is that the humans have thresholds of perception of motion parameters (linear and angular accelerations, angular rates). Within these thresholds the person, by means of vestibular apparatus, doesn’t feel it’s motion and respectively the change of aircraft flight parameters. The previously conducted research [1–5] have shown that the magnitudes of such thresholds depend upon a lot of factors. Among them the following could be pointed out:

- the magnitudes of aircraft current flight parameters (linear and angular accelerations, angular rates);
- presence of vibrations and acoustic noises, including landing gears and high lift devices extension/retraction, engines operation mode change, etc.
- presence of external disturbances – turbulence, high lift devices extension asymmetry, change of aircraft trim conditions and so on;
- aircrew psychophysiological state.

Under conditions when flight parameters values are inside thresholds there is a possibility of some contradiction between pilot’s feelings and information from flight deck instruments because pilot doesn’t receive information from one of the most important information source. For example, slow change of bank angle indications on attitude indicator at absence of roll rate perception could cause doubts on it’s operability that consequently increase pilot response time, raise aircrew psychophysiological workload etc.

Most of the researches of acceleration information perception by the pilot were carried out on ground based simulators with moving cockpit [1-4]. For a number of years there also were conducted in TsAGI the research on determination of the thresholds of human perception of g-loads and angular motion for all degrees of freedom (pitch, roll, yaw) in unified conditions and according to unified methodology. Results of these research made it possible to reveal the general rules of acceleration information perception from different channels and elaborate multisensory models of perception process, which account the share of different human sensor systems in the motion perception process [4]. However, it is impossible to reproduce in ground conditions the feeling of aircraft motion in the whole range of frequencies and to consider all peculiarities of the real flight, which could influence aircraft motion perception.

During perception thresholds determination on ground based simulators there usually are not reproduced such factors of real flight like vibrations, acoustic effects etc. These factors have similar in nature mechanical influences on corresponding receptors and thereby could roughen pilot sensitivity of linear and angular motion perception.

Heretofore some flight research were conducted in GFRI on flying test-bed Tu-154M №85317 on determination of g-load perception thresholds and magnitude of g-load influence on roll and pitch angular motion perception thresholds [5]. But these research were very limited in scope (3 flights), carried out by only one test-pilot and in a narrow band of g-loads (1÷1,5 g). But at aircraft entering in upset conditions and during recovery from upsets there could occur normal g-loads varying in a very large range – from values considerably less than 1 g up to maximum allowable values what may significantly affect acceleration information perception on other degrees of freedom.

Acceleration sensations arise simultaneously on various degrees of freedom in real flight. So, for example angular motions in roll and pitch channels arise as a rule simultaneously with normal g-load, which could reduce pilot sensitivity to angular motion. Thus data on thresholds of pilot sensitivity to aircraft motion parameters, obtained in real flight tests are very important first of all for it practical application. In this regard it was decided to continue flight research but on Ilyushin-103 aircraft.

IL-103, see Figure 1, is general aviation multipurpose aircraft. Maximum indicated airspeed in clean configuration V_{MO}=320 km/h, allowable normal g-load is in the range n_z=0,5…3,5 g, what is substantially wider than analogous envelope for large transport aircraft.

Fig. 1. Ilushin-103 aircraft.

For research purposes the aircraft was instrumented with onboard system of flight parameters measurements and recording. Onboard aircraft there were installed a video recording system and special joystick with 4 buttons which pilot should press at the moment when he starts to feel the aircraft motion.

2 Flight research technique

During flight research the aircraft take-off weight was G = 1265 kg with fuel weight 40 kg. Center of gravity position at take-off was $\overline{X}_T$≈28,3 % MAC (mean aerodynamic chord). Maximum allowable center of gravity rear position of $\overline{X}_T$=31 % MAC.

Flight tests trials were carried out in the range of altitudes H = 500.1500 m and indicated airspeeds V_{IAS}=200…320 km/h in clean configuration. Aircraft was controlled by the left-hand pilot during flight research modes. At the beginning of each flight test mode a right-hand pilot had kept his head in normal position closed his eyes, released the aircraft controls (control stick and rudder pedals) and took a joystick at his hands.

Initially a refinement of roll motion pilot perception thresholds under unit normal g-load, i.e. at horizontal straightforward flight was made. Left-hand pilot performed control stick deflections in roll channel in such a manner that bank angle change was as close as possible to the following sinusoidal shape with gradually progressive amplitude:

$$\phi(t) = A_{\phi}(t)\cdot sin(\omega\cdot t) \quad (1)$$

where:

$A_{\phi}(t)$ and ω – amplitude and frequency of sinusoidal bank angle variation.

Flight research modes were conducted for three values of frequency: ω = 2, 1 and 0,5 1/sec starting with maximum frequency and for three values of roll control inputs amplitude. Engine operation mode was set to be corresponded to trimmed horizontal flight without bank and sideslip angles. At the moment of the recognition of roll motion availability and direction the right-hand pilot pushed the correspondent button on the special joystick and reported left-hand pilot about the end of a trial.

Next, a refinement of roll motion pilot perception thresholds under presence of normal g-load not equal to 1 g was performed. To fulfil flight modes with g-load values of n_z=+1,5…+3,5 g there were executed the windup turns with descent (to maintain the specified airspeed). Pull-up ("zoom") maneuvers were performed to determine the pilot roll motion perception thresholds under g-load values of n_z<1,0 g.

Refinement of normal g-load pilot perception thresholds initially was carried out in straightforward horizontal flight at engine operation mode corresponded to corresponded to trimmed conditions. Left-hand pilot deflected control stick in longitudinal direction in such a manner that normal g-load variation was as close as possible to the following sinusoidal shape with gradually icreasing amplitude:

$$n_z(t) = 1 + A_{n_z}(t)\cdot sin(\omega\cdot t) \quad (2)$$

where:

$A_{n_z}(t)$ and ω – amplitude and frequency of sinusoidal g-load variation.

Flight test modes were conducted for two values of frequencies ω = 0,5 and 1 1/sec. In case of bank angle occurrence during flight test mode execution it was eliminated with minimum roll rate.

Refinement of normal g-load pilot perception thresholds in case if initial g-load is not equal to 1 g (pilot perception threshold of g-load variation) was carried out by means of windup turns execution with g-load values of n_z=+1,5…+3,5 g.

Three test-pilots participated in flight research as evaluation pilots (right-hand pilots). Each pilot conducted 5 test flights.

3 Flight research results

Determination of roll motion pilot perception thresholds for upset conditions was performed basing on the results of secondary processing of flight research data obtained in valid test flights. The validity of a particular test flight was determined by right-hand pilot basing on his own feelings of readiness to aircraft motion perception and assessment, wright understanding of the flight test task, skills of fast and confident finding and pushing of appropriate buttons on the special joystick with closed eyes.

3.1 Roll motion sensitivity thresholds

The results of the experiments to determine sensitivity thresholds on the background of the G-load equal n_z=1 are presented in Figure 2 for all the pilots. The data presented are magnitudes of the angular rates as a function of the frequencies considered in the experiments. The dash lines in the figure envelope the area of the minimal roll rates ($A_{p\ thresh}$) registered by pilots when they felt the roll motion; the solid line shows the averaged values of roll rate magnitudes ($A_{p\ aver}$).

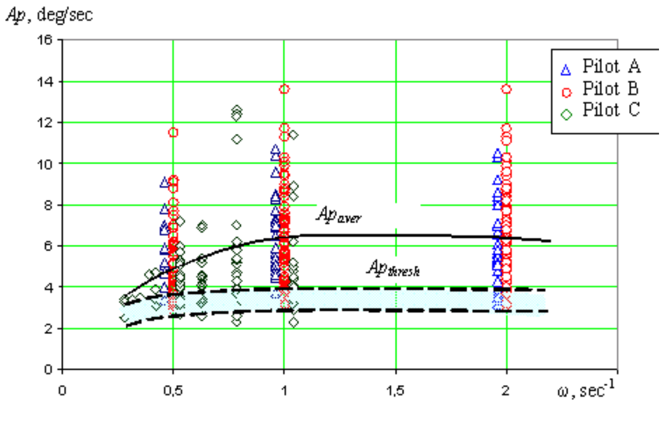

Fig. 2. Magnitudes of the roll rates as function of the roll motion frequency at n_z = 1; the data were registered at the moment a pilot pushed special button.

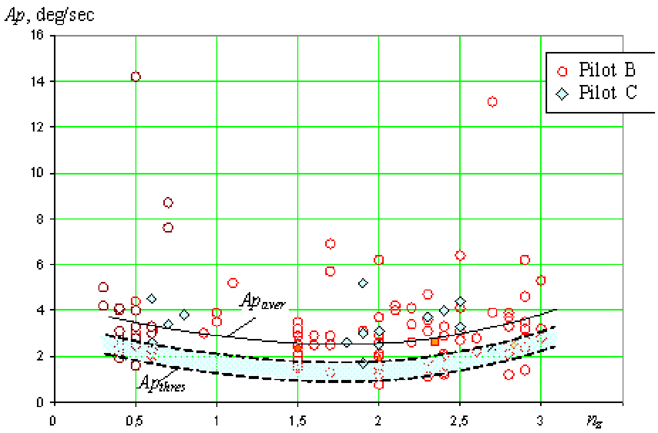

Fig. 3. Effect of G-load on roll rate sensitivity thresholds at frequency ω=1rad/s.

It is seen that the values of the roll rate magnitudes have considerable dispersion, since there are shown all data corresponding to the every event of pilot's pushing the registering button. Thus we can suppose that there are as well the magnitudes much exceeding the threshold level. This is due to the fact the roll motion in the experiment was reproduced manually with simultaneous monitoring and controlling the other aircraft state parameters (G-load, flight speed, sideslip, etc.) and, thus, a pilot could hardly maintain the slow increasing of the roll motion amplitude. Besides, the flights were performed at the low altitude in turbulence, which could hamper the sensations as well.

Nevertheless, it is seen from Figure 2 that the roll rate threshold values differ from pilot to pilot and depend on the roll motion frequency. The greatest sensitivity threshold is about 4.5 deg/s, the lowest is about 3 deg/s at frequency 1 rad/s. All the pilots show the common tendency to decrease sensitivity thresholds with decreasing roll motion frequency below ω=1 rad/s.

3.2 Roll sensitivity thresholds as a function of the G-load

Most experiments were conducted for two roll motion frequencies: ω=0.5 rad/s and ω=1 rad/s. Considered G-load range was different for pilots. Experiments with Pilot C were conducted as well for frequencies ω=0.628 rad/s and ω=0,785 rad/s.

Figure 3 demonstrates results received at roll motion frequency ω=1 rad/s for two pilots (B and C). The results received for the other frequencies are similar to that shown in Figure 3. The data include all roll rate magnitudes registered by pilots. Similar to Figure 2, the lines show the averaged sensitivity thresholds ($A_{p\ thresh}$) and the area of the minimal thresholds.

The data show that the roll motion thresholds are different for different pilots and depend on the G-load level. The G-load exceeding n_z=1 and decreasing below n_z=1 leads to sensitivity threshold increasing. The most interesting case from practice point of view is that corresponding to G-load increasing, which can occur, for example, in upset recovering. The considerable data dispersion does not allow accurate approximation of the function, but the tendency of the sensitivity thresholds to vary with G-load exceeding over n_z=1 can be described as follows:

$$P(n_z)= P_{thresh1.5}\cdot K(1+A_{n_z}) \qquad (3)$$

where $p_{thresh1.5}$ is sensitivity threshold for n_z=1.5 at the considered roll motion frequency; K=1.5 is the gradient of the threshold increasing when G-load exceeds 1.5; A_{nz} is G-load increment over n_z=1.5. To define the function more accurate, the further experiments should be conducted with the aircraft capable to automatically reproduce the required roll motion.

3.3 Sensitivity thresholds to normal acceleration

Experiments were conducted to determine differential sensitivity thresholds ([6]) to the acceleration variation relative to its background level. Most experiments were conducted with two pilots (B and C) for the two frequencies of the imposed acceleration: ω=0.5 rad/s and ω=1 rad/s. Pilot C performed experiments for two additional frequencies ω=0.628 and ω=0,785 rad/s as well, but the data is too scarce to be analyzed.

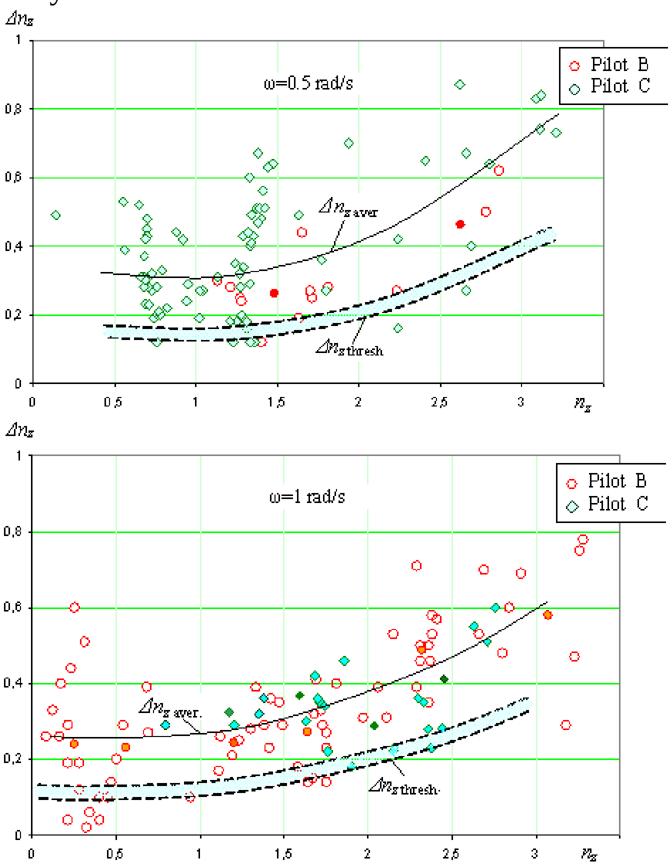

Fig. 4. Differential thresholds to sinusoidal acceleration as a function of the background acceleration for two frequencies of the imposed acceleration.

Results received for frequencies of the imposed acceleration ω=0.5 rad/s and ω=1 rad/s are shown in Figure 4. The figure shows magnitudes of the imposed acceleration registered by pilots as a function of the background normal acceleration. The dash lines are enveloping curves of the minimal thresholds, the solid line shows the averaged values of the thresholds.

It should be mentioned first of all that the in-flight data on the normal acceleration differential thresholds are absent in publications, which leads us to assume that the systematical data presented are received for the first time.

Figure 4 shows that differential thresholds of the normal acceleration differ for different pilots and depend on the background acceleration. For pilot C the minimal sensitivity threshold to the acceleration variation is $\Delta n_z \approx 0.12$ corresponding to frequency ω=0.5 rad/s for the background acceleration within n_z=0.7÷1.3. For pilot B the differential thresholds for the small values of the background acceleration $n_z \leq 0.5$ are less than for pilot B. The difference is determined by difference in pilots' age, flight experience, individual performance, etc. Nevertheless, their common tendency is the increase of sensitivity thresholds with the increase of the background acceleration. The tendency corresponds to the psychophysical law defined by German physiologist Weber. According to the law, the sensitivity threshold to the variation of the stimulus ΔI is proportionate to the value of the stimulus I [6]:

$$\frac{\Delta I}{I} = \text{const} \qquad (4)$$

The expression was then improved by physicist Fechner, who defined the intensity of the sensation S as a function of the stimulus I causing the sensation:

$$S = a \cdot \ln I + b \qquad (5)$$

where a and b are constants different for different types of stimulus and channels of perception. The formula is the mathematical expression of the psychophysical law named after Weber-Fechner.

It should be mentioned that the psychophysical law is true only if the intensity of the stimulus is not very strong or very weak. At present, the more accurate formula to determine the stimulus sensation is that defined by Stevens:

$$S = k \cdot (I - I_0)^n \qquad (6)$$

Where I is the value of the stimulus, I_0 is the value of the absolute sensitivity threshold of the stimulus; k and n are constants different for different stimulus.

Analysis of the data presented in Figure 4 show that the average values of acceleration increments $\Delta n_{z\ aver}$ felt by a pilot are twice as much greater than the minimal acceleration increments, which are, in fact, the threshold values of the acceleration increments $\Delta n_{z\ thres}$. The fact allows us to use the function of the average acceleration increments to calculate the function of the threshold acceleration increments.

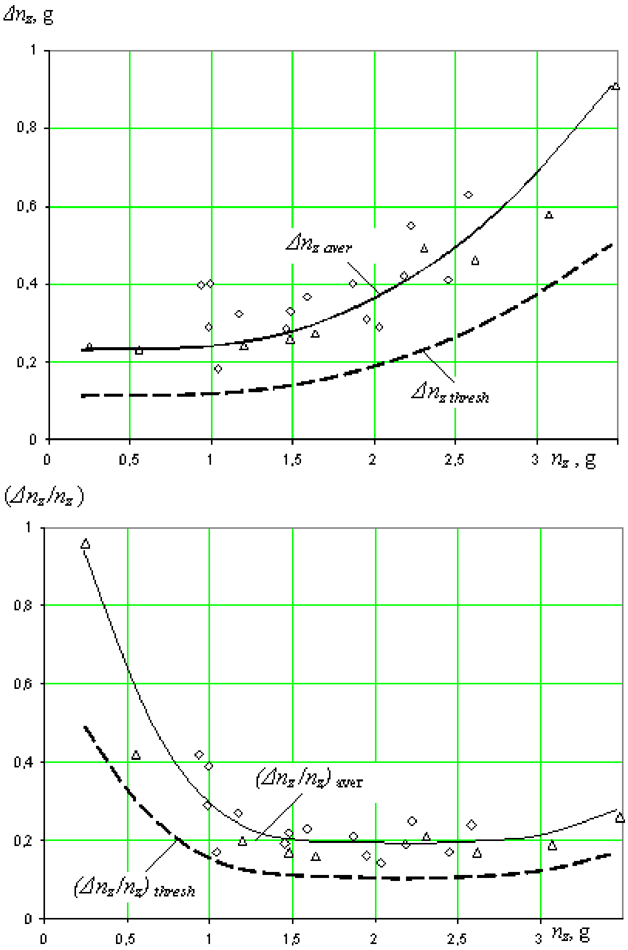

Fig. 5. Absolute $\Delta n_{z\ thresh}$ and differential $(\Delta n_z /n_z)_{thresh}$ sensitivity thresholds to normal acceleration increment as a function of the background acceleration.

The result of the calculation is presented in Figure 5, which shows the absolute $\Delta n_{z\ thresh}$ (upper figure) and differential $(\Delta n_z\ /n_z)_{thres}$ (lower figure) values of the sensitivity thresholds. It is seen that the differential threshold for the normal acceleration within n_z=1÷3 g does not practically change, which meets the Weber-Fechner law. Thus, the value of the differential threshold calculated is about 10 percent of the background acceleration.

4 Conclusions

1. The in-flight tests conducted have clarified and broadened out the experimental database on the absolute and differential sensitivity thresholds to linear and angular aircraft motion.
2. A unique experimental database is collected on the effect of the normal G-load on the angular motion sensitivity thresholds, for the wide range of G-load variation including n_z<1. It is shown, in particular, that both G-load increasing and decreasing lead to angular sensitivity thresholds increasing. The expression to assess the tendency is proved by the experimental data.

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