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UPSET RECOVERING SIMULATION TO ENHANCE FLIGHT SAFETY BY ON-GROUND PILOT TRAINING

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Abstract

Three main aspects of on-ground upset recovering simulation is considered: aircraft mathematical model to take into account unsteady aerodynamics; simulator drive algorithms improvement and modifications to take into account the peculiarities of the motion cues arising in upset/stall and recovering; and indication to the pilot of the current angle-of-attack and G-load.

1 Introduction

Recent years, the loss of control became the reason for the most of flight accidents counting 2573 fatalities in 87 accidents world-wide [EASA Safety Review 2006]. It can be fully attributed to the lack of pilots' training in early detection of the aircraft upset and in control actions to recover from the upset/stall. Thus, in a world-wide aviation community there is mutual understanding of the importance of on-ground pilot training for upset avoidance, recognition, and safe control activity for upset recovering.

LOC is defined as an abnormal flight condition that is characterized by the following behaviors:

- aircraft motion not predictably altered by pilot control inputs;
- nonlinear effects such as kinematical/inertial coupling, disproportionately large responses to small state variable changes, or oscillatory/divergent behavior;
- high angular rates and displacements;
- difficulty or inability to maintain heading, altitude, and wings-level flight.

Thus, on-ground simulation of the critical flight modes is a challenging problem, which requires a number of non-trivial tasks to be solved. First, there are no adequate mathematical models of aircraft describing its behavior beyond standard flight envelope. Taking into account the lack of wind tunnel data at high angles of attack for transport aircraft, the routine procedure of the model development turns into a "piece of art".

Second, the hexapod-type simulators, which nowadays are widely used in aviation training centers, have serious limitation in reproduction of some motion cues typical of the upset recovering maneuver. So far, there is no clear understanding if the limitations can affect pilot training or distort simulation results.

Third, in pilot's disorientation, an important role plays inadequate or incomplete flight dataware on the aircraft attitude and flight parameters. The angle of attack indicator is the only one which presents the direct visual information to the pilot about the aircraft state in upset, but many civil airplanes are not equipped with the indicator, and there is no any coordinated view within aviation community on its necessity.

2 Aircraft Model

The key aircraft state variables in identifying LOC are the angle of attack, sideslip, Euler angles (pitch and roll), structural load factor, airspeed, and the behavior of the aircraft with respect to the control commands. Airplane upset, is commonly described as a situation where the aircraft is unintentionally brought outside of its normal flight envelope. Airplane upset can often develop into a LOC condition. The types of airplane upset range from large attitude excursions to the more serious situations involving stall. Numerous factors can lead to airplane upset: pilot error, environmental disturbance such as wind shear and wake turbulence, flight system failure, or a combination of these.

Several upset prevention and recovery strategies are currently being considered: development of advanced flight control technology, advanced warning and advisory technology and pilot training programs. Advanced flight technologies, such as the flight envelope protection system, can be effective in preventing accidents in some scenarios. However, as long as pilots remain the chief commander in flight, they also need to be trained to effectively recognize and respond to unusual situation. Conducting flight tests and training in upset conditions is impractical due to the high risk and cost. A more practical option is to use ground-based flight simulators, which are safe, inexpensive to run, easily accessible, and have played crucial role in pilot training for years.

Researchers, however, have been concerned with two critical shortcomings of using current ground-based flight simulators for upset recovery training. One of the shortcomings is that most flight model aerodynamic databases only cover the aircraft's normal flight envelope. Analysis of LOC accident data however shows that airliner can exceed the boundaries of the normal envelope in the course of an upset event (Fig. 1).

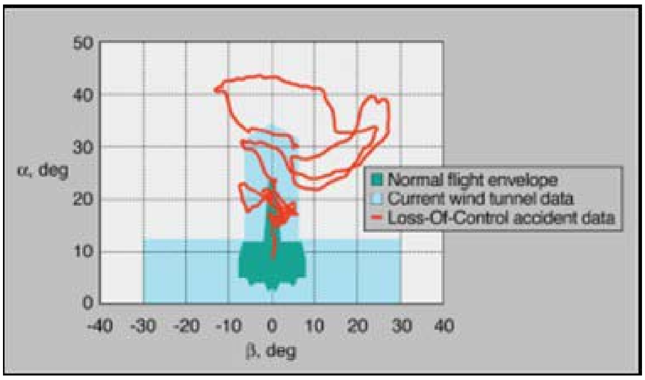

Fig. 1. LOC accident and data envelopes.

Using the flight model outside of its aerodynamic database requires extrapolation, which would most likely result in inaccurate aircraft response and could in turn lead to negative training.

The second shortcoming of the current ground-based flight simulators is the fidelity of the motion produced in upset conditions. Even with an enhanced aerodynamic database covering a larger flight envelope, it is unknown if the hexapod motion system used in most simulators will be sufficient to provide motion cues that can lead to positive transfer of training.

2.1 Extended Mathematical Model of Generic Aircraft

The generic airliner model was developed using MATLAB/Simulink© computing environment for TsAGI PSPK-102 flight simulator. The block-diagram of the simulation model is shown in Fig.2. The simulation model includes the block for computation of aerodynamic forces and moments with contribution from propulsion, equations of motion considering airplane as a rigid body and basic command and stability augmentation system (CSAS) for shaping controllability and stability characteristics at normal flight regimes to meet requirements for airliner handling qualities.

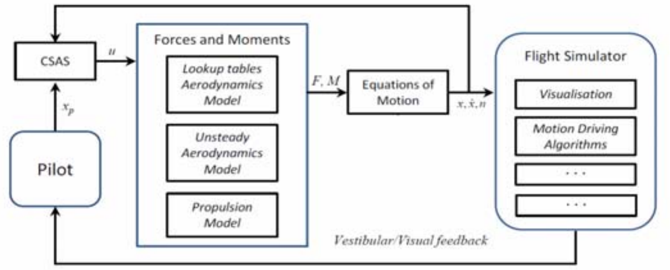

Fig. 2. Generic aircraft simulation model structure.

Basic extensions of traditional aerodynamic model were taking into account all wind tunnel aerodynamic dependencies obtained beyond normal flight envelope for high angles of attack and sideslip, inclusion of rotary balance experimental data for high incidences and introduction of unsteady aerodynamic effects connected with flow separation delay.

Increase of angle of attack above some critical value leads to stall which is associated with onset of flow separation over an area of the wing. A sudden loss of lift and nonlinear transformation in the pitching moment coefficient are typical consequences of flow separation. Stall conditions may produce strong dependence of the aerodynamic loads on prehistory of motion. Fig.3 shows variation in the normal force coefficient in static conditions (solid circles) and during forced oscillations with a number of non-dimensional frequencies k and large amplitude of oscillations (empty markers). Increase of angle of attack leads to significant delay of flow separation and increase in maximum lift, while during decrease of angle of attack separated flow conditions are continued to lower angles of attack region. Such dynamic hysteresis can produce negative damping in the pitching moment. In the lateral/directional mode stall leads to deterioration of the rolling and yawing moment coefficients negatively affecting airplane stability and control effectiveness.

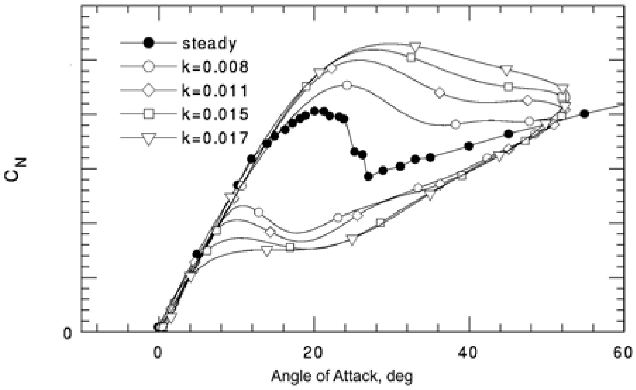

Fig. 3. Normal force at stall conditions: static and dynamic dependencies.

The following assembly of the aerodynamic model is applied using the lookup tables aerodynamic data interpolation from static (ST), rotary balance (RB) and forced oscillation (FO) tests [1, 2]

$$C_i = C_{iST}(\alpha,\beta) + \Delta C_{iRB}(\alpha,\beta,p_a) + \ldots$$
$$\Delta C_{iST}(\alpha,\beta,\delta_i) + C_{iq_aFO}(\alpha)q_a + C_{ir_aFO}(\alpha)r_a \cdot$$

Here i is X, Z, l, m or n and δ_j is elevator, stabilizer, rudder, ailerons or spoiler deflection.

Unsteady aerodynamic effects at stalled conditions require implementation of a special modeling approach. The unsteady aerodynamic contribution may be represented as additional aerodynamic term in the above aerodynamic lookup tables interpolation [1, 2]. For example

$$C = C(\alpha,\beta,p_a,q_a,r_a,\delta_j) + C_{Dyn}(t)$$

where the time dependent component in this expression is described by the ordinary differential equation shown below as a washout filter

$$C_{Dyn} = \frac{\tau s}{\tau s + 1}\Delta C(\alpha)\,.$$

Here τ is the characteristic time scale of separated flow development. Note that in static conditions term C_{Dyn} gives zero contribution to the total aerodynamic load. The aerodynamic model incorporates unsteady nonlinear variations of the above type in the vertical force and pitching moment coefficients.

The airliner has two turbofan engines whose thrust is included in aerodynamic forces and moments. The thrust characteristics are simulated by the look-up data tables depending on altitude, Mach number and throttle position. Dynamic characteristics of engines such as delay in response to throttle input and thrust increase/decrease rate limit are simulated by the second order dynamical system with saturation nonlinearities.

The block-diagram of generic airliner simulation model in Fig.2 includes also a basic command and stability augmentation system (CSAS) for providing airplane required controllability and stability characteristics for normal flight regimes. In the longitudinal channel the aircraft is controlled by means of elevator and stabilizer. The stabilizer is used only for trimming purposes and is deflected slowly. The required elevator deflection is defined by pilot longitudinal control input X_{lon} and feedback signals including terms proportional to the pitch rate and the normal load factor n_z. A nonlinear correction is used to compensate nonlinearity in the pitching aerodynamic moment in the pre-stall region of angles of attack. Euler’s angles are used for compensation of gravity terms. The lateral/directional channels are controlled by means of rudder, ailerons and interceptors.

Rudder is deflected proportionally with pedals X_{ped} and yaw rate signal sent through a washout filter. There is also an interconnection with lateral control input X_{lat}. Aileron deflection is proportional to the lateral control input X_{lat}. Interceptors are helping ailerons to improve controllability in roll, they are deflected when lateral control input exceeds some amplitude $|X_{lat}|> X_{lat^*}$.

In flight simulator the pilot perceives motion differently from that in real flight. The simulator motion cuing depends on kinematic constraints of flight simulator platform, visualization system and implemented motion driving algorithms1. A realistic simulation of vestibular cues during intensive large amplitude motion following the lateral/directional departure is hardly possible, however realistic visual simulation can allow experienced pilot to validate simulated motions and tune the model parameters to improve model fidelity.

3 Flight Simulation Aspects

The aircraft upset/stall is a rare, but very dangerous event. The majority of the pilots has never experienced such an event and have no idea about the nature of the motion cues arising in upset and upset recovering. Inadequate motion cueing or motion distortions introduced by drive algorithms can distort pilot's opinion and affect pilot training. That is why the motion fidelity in simulation of upset recovery maneuver is of great importance.

Achievement of the adequate flight simulation fidelity is determined by the successful reproduction of the useful motion cues and simultaneous minimizing of the false cues.

3.1 Reproduction of the Useful Motion Cues

3.1.1 Normal G-loads

Analysis conducted in the course of the SUPRA project of the 7th European Framework Program [3] showed that the motion cues arising during upset and upset recovering are of very low frequencies. Reproduction of the low-frequency motion cues on hexapod simulators is either accompanied by large distortions or impossible due to simulator technical limitations (Fig.4). Indeed, the normal G-load arising during aircraft upset recovering approach 1.5 g and more. Thus the question arises whether the G-load inadequate reproduction can affect simulation results and pilot training.

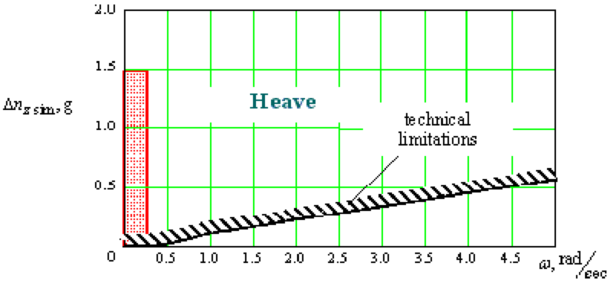

Fig. 4. Limitations for hexapod-type simulators to reproduce normal G-loads.

It is known from the flight dynamics theory that the entire flight mode range can be divided into two ranges depending on the flight speed: one is G-load-controlled range, the other is the pitch-controlled range. The flight velocity which divides the ranges equals approximately V_0=140 m/s (~500 km/h). This principle is the basis for a few handling quality criteria to select optimum, from pilot's point of view, aircraft dynamic performance [4] and control sensitivity characteristics [5] depending on the flight mode. The criteria assume that if the flight speed is low and the G-loads are relatively small, the pitch motion is the determining for the pilot to control an aircraft and to select aircraft characteristics, and vice versa, if the speed and G-loads are high, the G-load variation is determining for the pilot to control an aircraft. Fig.5 shows time histories of the flight speed in different scenarios of upset recovering maneuver. It is seen that the most part of time the flight speed corresponds to pitch-control flight mode. G-loads arise by only the final stage of upset recovering.

Studies show that pilots' adaptation time to the small G-load is pretty short. According to [6], the duration of the G-load sensation depends on the G-load level: for G-loads of about n_z=1.1-1.2 the G-load sensation disappears in 2-4 seconds. But for n_z=1.5-2.0 the sensation disappears in one and even more minutes. It means that the pilots can not fully adapt to the G-loads arising in upset recovering, since the total time of the maneuver is less than one minute. Nevertheless, the data received earlier in centrifuge of “Zvezda” Enterprise (Fig.6) show that such G-loads do not worsen tracking accuracy.

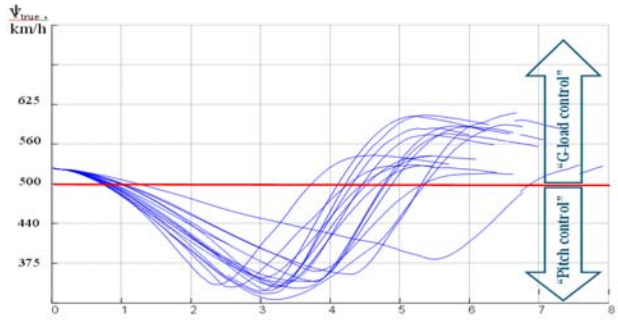

Fig. 5. Flight velocities in upset/stall and recovering (different scenarios).

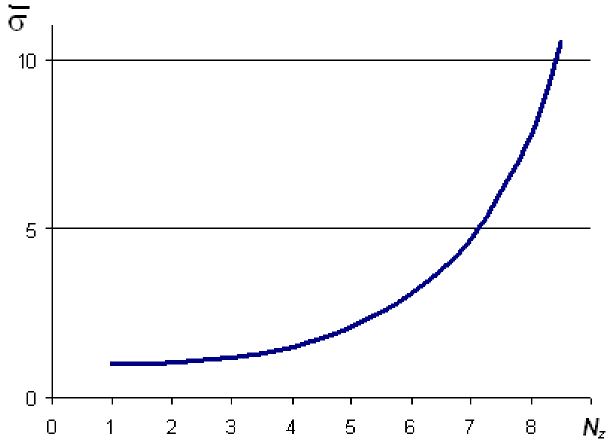

Fig. 6. Tracking accuracy as a function of the G-load.

Thus, the analysis above allow us to suppose that the low capabilities of the 6DoF simulators to reproduce G-loads typical of the upset recovering can not considerably affect the simulation results and pilot training.

3.1.2 Angular Motion

Reproduction of the angular motion typical of the upset recovering has its limitations as well, which are determined by both technical limitations and, in addition, by the false cues arising while cockpit rotation (Fig.7). Nevertheless, the reproduction of the angular can approach adequate level of fidelity.

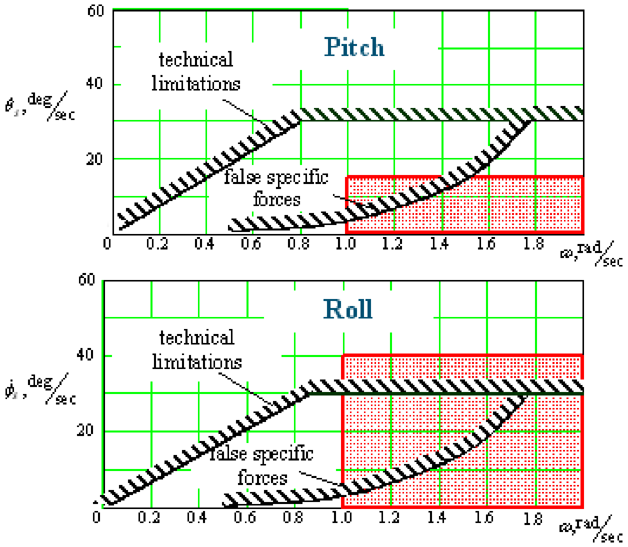

Fig. 7. Limitations for hexapod-type simulators to reproduce angular motion typical of upset recovering maneuver.

The arising false cues of the linear accelerations distort reproduction of the angular motion and lead to pilots’ disorientation. References [7-9] show that to reduce the false sensation of the linear accelerations, the signals of the reproduced roll (pitch) rates should be scaled down. According to [8], to approach the adequately high level of the angular motion reproduction, it is sufficient to provide root-mean-squares of the angular rates to be just 2-3 times greater than their sensitivity threshold values (Fig.8).

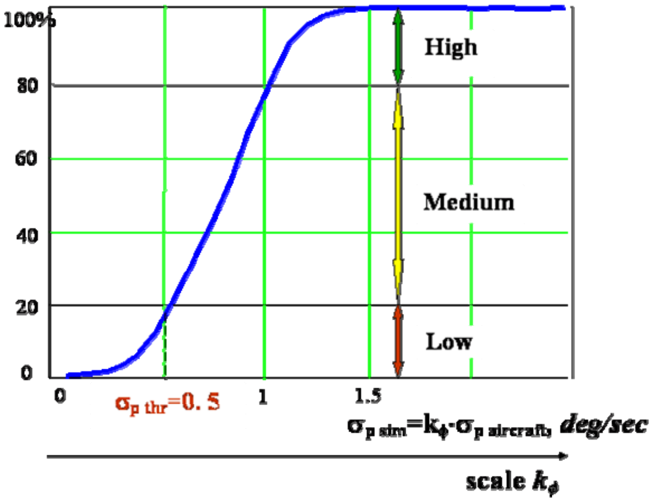

Fig. 8. Effect of angular rates scaling on the angular motion reproduction fidelity.

The curve in Fig.8 is derived from the experimental data demonstrating the pilot performance (disturbance task accuracy and pilot ratings) as a function of the roll rate scaling. The curve in Fig.8 can be divided into three characteristic regions. In the first region with scaling increasing from $k_\phi=0$ to a certain value, the motion fidelity is low and corresponds to fixed-base case. This is due to the fact that the simulator angular motion is below the sensitivity thresholds. When the scaling exceeds the value corresponding to the threshold level of the angular motion sensations (second region, $\sigma_{p\ \mathrm{thr}}>0.5$ deg/s) the motion fidelity increases abruptly up to the highest level. This is due to the fact that the scaling increase provides greater volume of the motion cues (increase of motion cues duration and frequency of their exceeding the threshold level). In the third region the motion fidelity does not noticeably improve regardless of the significant scaling up. It means that the piloting accuracy and pilot ratings do not practically improve in this region. This is due to the fact that the further upscaling leads to increase of motion intensity only, not to their frequency of arising and duration. But the motion cues intensity does not affect the amount of information the pilot perceives from motion cues, which is similar to that that the volume of sound does not affect the content of message. In the third region the pilot responds to the motion cues intensity increasing (or decreasing) with his/her correspondent increasing (or decreasing) control activity. Thus, in the third region of the curve (Fig.8) the pilot control activity does not depend on the angular motion scaling.

3.2 Minimizing of the Reproduction Distortion and False Cues

3.2.1 Distortions Introduced by Drive Algorithms

Motion distortions introduced by drive algorithms can distort pilot's opinion and affect pilot training. At present there are no in publications any recommendations on the distortions minimization. Thus, we can recommend the criteria developed earlier in [3, 8].

Unfortunately, false cues arising due to high-pass filters are inevitable. While modeling large-amplitude angular motion two types of false cues arise: the false specific forces due to cockpit tilting, and false cues of opposite sign. The two types of the false cues can arise independently or simultaneously depending on simulator travel capabilities. Their integrated effects on motion fidelity are shown in Fig.9.

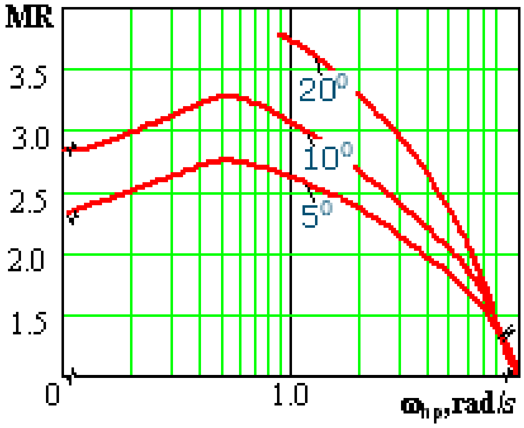

Fig. 9. Motion fidelity criteria to avoid false cues in angular motion reproduction.

The data are functions of simulation fidelity ratings (MR – Motion Roughness, [8]) versus high-pass filter frequencies for various bank angles capture tasks without scaling. At low frequencies the simulation fidelity worsening is mainly due to false specific forces. Here, the cockpit tilt angles are almost equal to aircraft bank angles, while at the same time false opposite roll rates are insignificant. As the filter frequencies increase, the tilt angles and, consequently, the false lateral accelerations decrease, but the false roll rates opposite in sign increase; thus, as filter frequencies increase simulation fidelity is increasingly determined by false roll rates opposite in sign.

In accordance with the curves in Fig.10, the minimization of false cues effect can be done by adjusting the high-pass filter frequency or by downscaling the filter gain.

3.2.2 Distortions of the Angular Motion Reproduction Caused by the G-load Effect

The distortions caused by drive algorithms are not the only ones which can be attributed to the false cues. The deliberate reproduction of the sensations which are not felt in real flight can be attributed to the false cues as well. For example, in [3, 10] it was shown that the normal G-loads can affect the motion perception.

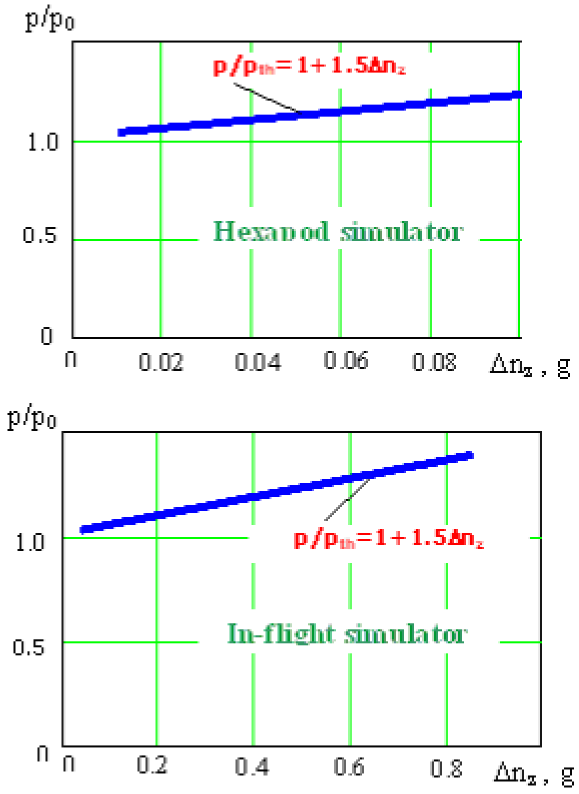

Fig. 10. Effect of normal G-load on the perception of angular motion.

The data presented in Fig.10 are for roll axis; the similar functions are available for pitch and yaw axis. It is seen that the normal G-loads noticeably affect angular motion perception. The function can be approximated by the following expression (for the roll):

$$p/p_0 = 1 + k \cdot \Delta n_z\,, \qquad (1)$$

where p_0 is the absolute threshold value at the particular frequency, Δn_z is normal acceleration increment.

Experiments were conducted for different frequencies of angular and linear motion: ω_{nz} = 0.5 rad/s, $\omega_{p,q}$ = 2 rad/s; ω_{nz} = 0.2 rad/s, $\omega_{p,q}$ = 0.5 rad/s. Nevertheless, the functions received appeared to be similar to each other regardless of the motion frequency. It means that coefficient k can be assumed independent of motion frequency and equal k=1.5.

According to (1), as normal G-load increases from 1 to 2.0-2.5 g, the angular motion thresholds increase by factor 2. It means that the reproduction of the angular motion regardless of the G-load effect can result in false cues reproduction and wrong pilot training.

To take into account the effect of G-loads, an adaptive coefficient is implemented into angular motion cueing algorithm (high-pass filters paths), which reduces reproduced angular rates in accordance with the following expression:

$$k = \frac{1}{1 + 1.5\left|\Delta n_z\right|}\,.$$

4 Indications of Flight Parameters

Inadequate or incomplete pilot's indication of the aircraft state and flight parameters can contribute to pilot's disorientation. The present work shows recent results received on the effect of angle-of-attack and G-load indicator on the effectiveness of the upset recovering. The basic notions for the work are as follows below.

At present in the civil aviation there are two methods of the *direct* indication of approaching the critical flight modes: control inceptor shaker and angle-of-attack display. The shaker gives the direct haptic information to the pilot and, in this sense, it is more preferable than so-called "force stops", which can be easily overdriven by a pilot; the "force stops", in addition, are ineffective for the short-travel control inceptors like sidesticks. But nevertheless, indication of the angle of attack as the main cause of the aircraft upset could be useful for airplanes both equipped and unequipped with control inceptor shakers or any other types of tactile information. The process of the perception and recognizing of any other *indirect* information about the angle of attack takes certain time, which can insufficient in critical modes.

The presented work is the first attempt to show the usefulness of the angle-of-attack indication.

4.1 Experimental Procedure

Experiments were conducted on TsAGI PSPK-102 flight simulator with 6DoF motion system.

The drive algorithms were tuned to better reproduce the motion cues typical of the upset recovering. The aircraft model corresponded to that developed in the course of SUPRA project [1, 2]. The upset scenario corresponded to the left or right wing upset; the intensity of the upset varied.

Five test pilots participated, who have rather extensive experience in in-flight upset/stall tests.

Piloting task begins at altitude 3 km, clean configuration, flight speed 460 km/h. Autopilot and autothrottle are disengaged. The pilot task was:

- Slowdown up to upset;
- Start upset recovering avoiding the secondary upsets and not exceeding the permitted G-loads.

The traditional column/wheel was used as a control inceptor.

According to the pilots' comments, the inceptor shaker gives the tactile information, which is directly perceived by a pilot regardless of his/her workload with other control activities. Thus, most tests were conducted with the shaker in order to assess the effect of the additional information from the angle-of-attack (AoA) and G-load indicators.

The following indicator configurations were considered:

- Shaker alone (S)
- Shaker + AoA (S+A)
- Shaker + G-load (S+G)
- Shaker + AoA + G-load (S+A+G)
- AoA + G-load (A+G)
- AoA alone (A)
- Without indication at all (N)

Fig.11 shows indicators of AoA and G-load on the primary flight display (PFD).

Both subjective and objective criteria were used. The objective criteria were

- To assess AoA: the number of the secondary stalls;
- To assess G-load: maximum altitude loss while recovering.

Subjective criteria were:

- Pilots' comments.

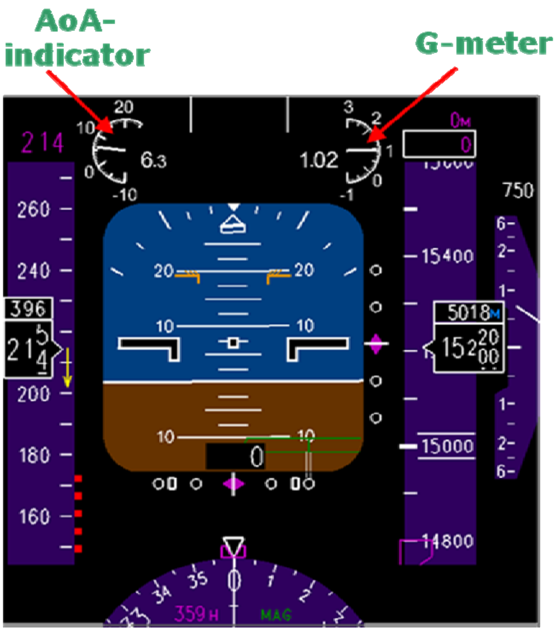

Fig. 11. AoA and G-load indicator locations on PFD.

4.2 Experimental Results and Discussion

Effect of AoA indication. To objectively assess the advantages of the AoA indicator, a number of the secondary stalls were used. Fig.12 shows the results received. It is seen from the Figure that all pilots reduce the number of the secondary stalls when AoA is displayed: for some of them the secondary stalls did not arise; for the others the number of stalls reduced in half. The results received confirm the effectiveness of the AoA indication.

In addition to the objective criteria, the pilots' comments were as follows:

- Information on the current angle of attack helps to prevent the secondary airplane stall, since it gives an idea about the angle of attack tendency (dynamics)
- Angle of attack display simplifies piloting and helps to select the adequate control strategy for upset recovering.

According to the pilots' comments, the AoA indicator provides a pilot with information about angle of attack increasing or decreasing, which help a pilot to correctly estimate the flight situation and choose the adequate control strategy: at the small AoA the upset recovering can be performed with a wheel; the high AoA can be dealt with pedals, since ailerons are ineffective.

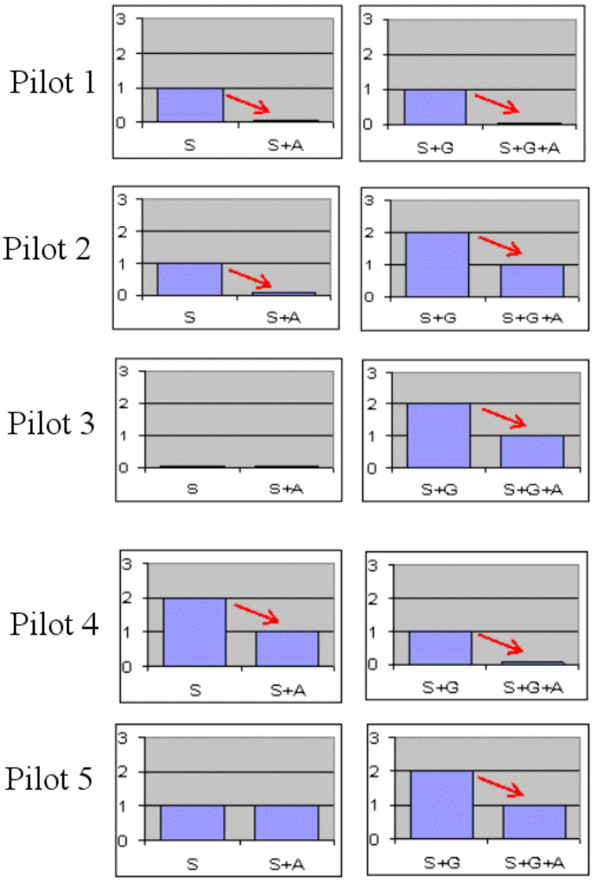

Fig. 12. Number of secondary stalls while upset recovering for different configurations of the displays (S and S+A, S+G and S+G+A).

Thus, we can conclude that the AoA indicator is an effective display to prevent airplane upsets and to recover safely from upsets. The indicator can be an alternative for the inceptor shaker of the airplane is not equipped with the latter.

Effect of G-load indication. As a rule, all modern airplanes are protected from the permitted G-load exceeding by automation system and, thus, there is no necessity in G-load indication. Nevertheless, as our experiments have shown, the G-load indicator can be very useful.

As some studies show, pilots can not adequately estimate the level of G-load they sense. First, the level of G-loads arising while upset recovering is relatively low – less than 2.0-2.5 g. As it was shown in Fig.6, this level of G-load does not affect pilot's workability. Second, the perception of such G-loads can be further dulled with the pilot's stress.

Besides, some experiments to train pilots to estimate the level of the G-load show that pilots forget their G-load sensations and fail to correctly assess its level in a month or two after the centrifuge the experiments. This fact, by the way, benefits to the 6DoF flight simulators as compared to the flight simulators equipped with centrifuges.

Let's consider now effectiveness of the visual indication of the G-load and its effect on the upset recovering characteristics.

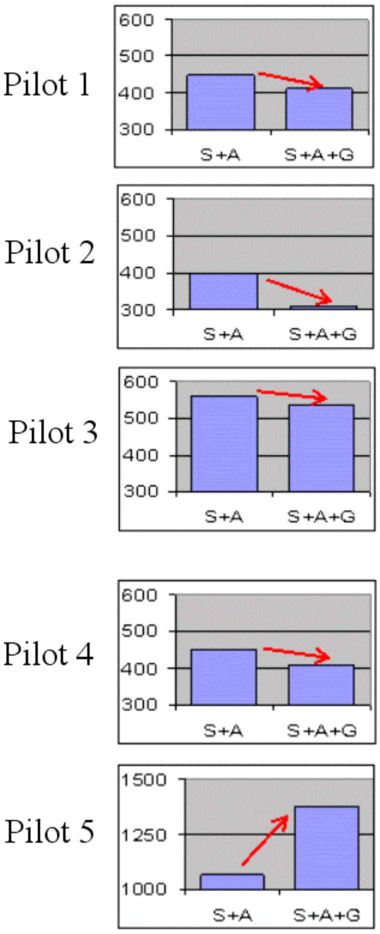

Fig. 13. Effect of G-load indication on the altitude loss while aircraft upset recovering.

Experimental data received are shown in Fig.13. It was said above that the integral criterion to assess the effect of the G-load indicator is the loss of altitude while upset recovering. We analyze the experiments in which the AoA was presented in order to exclude the cases with the secondary stalls, which could increase the altitude loss. It is seen that the four from five pilots reduced the altitude loss when the G-load was displayed.

It should be mentioned that the maximum G-loads arising while upset recovering did not exceed 1.8 g in our experiments. In other words, the G-load did not exceed the values limited by the automation. It means that the G-load indication is useful regardless of whether G-load is automatically limited or not.

Unlike the objective measures, the pilots are unanimous in their comments:

- The G-load indicator is useful since it reduces the altitude loss and helps to optimize the upset recovery trajectory.

5 Conclusions

1. A mathematical model of unsteady aerodynamics of generic airliner in extended flight envelope was developed and installed in TsAGI PSPK-102 flight simulator. In the mathematical model, the dynamic effects of flow separation/reattachment as well as the effects of aircraft possible intensive rotation ay high angles of attack were included. The model can be used for pilot training in stall prevention and upset recovery.
2. Analysis shows that the G-loads typical of upset recovering maneuver can not considerably affect pilot performance and, thus, the low capabilities of the 6DoF simulator to reproduce G-loads can not considerably affect pilot training.
3. Despite of the inevitable false cues arising due to drive algorithms, the good fidelity of angular motion simulation is achievable according to the criteria developed earlier.
4. To avoid reproduction of the false cues, drive algorithms should be modified to take into account the effect of normal accelerations on angular motion perception.
5. Angle-of-attack indication is useful and effective, which is confirmed by the objective measures and pilots’ comments. In addition to the warning effect, the AoA indicator provide a pilot with information about the angle of attack developing, which is very important for the pilot to choose the adequate control strategy while upset recovering.
6. G-load display is a useful indicator to train pilots to control the arising G-loads, which can be very important at the high flight speeds. Greater experiments are needed to receive more reliable data on the indicator effectiveness for the other upset scenarios.

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