FLIGHT TESTS OF TRANSPORT AIRCRAFT UPSET RECOVERY TECHNIQUES AND THE SYSTEM OF INFORMATION SUPPORT OF CREW

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Abstract

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. Presented in the report is short description of the results of flight research on the problems of the large transport aircraft upset recovery techniques and of the System of Information Support of Crew conducted by test-pilots and specialists of the Federal State Unitary Enterprise the "M.M. Gromov Flight Research Institute" (GFRI). Test flights were carried out in the frame of national scientific research activities and of the project "Simulation of UPset Recovery in Aviation" (SUPRA) funded under 7-th Framework Program of the European Commission.

1 Introduction

Upset position of the transport aircraft is understood as its entering in attitude position with pitch and bank angles, which values are outside the region allowed in normal flight operation. It demands an immediate recovering of the aircraft from upset as the further increase of pitch and bank angles during recovery from upset can result in exceeding of limitations on airspeed (Mach number) or on a normal g-load n_z or on an angle of attack (AOA) α with subsequent entering in a stall or spin.

Currently aviation community defines upset conditions as following: "An upset is defined as an airplane in flight unintentionally exceeding the parameters normally experienced in line operations or training: pitch attitude greater than 25 degrees nose up or 10 degrees nose down, bank angle greater than 45 degrees, or within these parameters, but flying at airspeeds inappropriate for the conditions".

Shares of accidents in Russia, related to civil aircraft entering in upset positions and stall from their total number for the different periods of operation are given on Fig.1.

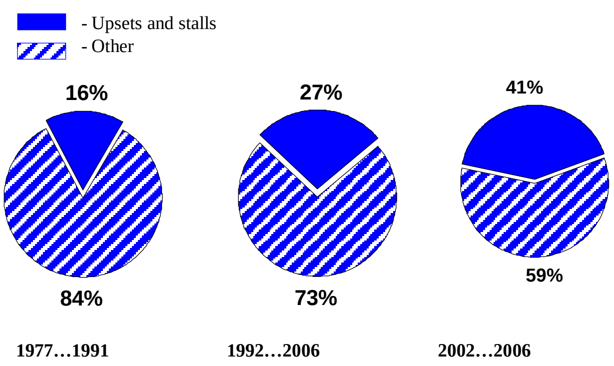

Fig. 1. Shares of accidents, related with civil aircraft entering in upsets and stalls from its total number for different exploitation periods.

Among the last well-known accidents in our country it is worth to mention accidents with B-737 aircraft near Perm, Tu-154 near Donetsk, A-320 near Sochi. The facts of these aircraft entering in upset conditions are confirmed by the results of investigation commissions' work. The correspondent statistics and relevance of upset problem throughout the world is also addressed in various reports of our European colleagues in different workshops and conferences. However it could be noticed that according to preliminary results of A-330 accident over Atlantic Ocean investigation, appeared in mass media, the reason of this accident is also entering in upset. Analysis of the statistics also demonstrates that this problem couldn't be certainly attributed to old aircraft only. Among the accidents mentioned there are very modern aircraft, featuring high level of manual flight control automation with critical flight parameters limiters intended for flight safety increase.

2 Upset recovery research areas

2.1 Possible ways of problem solution

The analysis of the reasons of erroneous crew actions at entering in upset and stall reveals that there is no unique prescription to solve this problem. But the majority of aviation specialists have a common understanding about the directions of actions which can if not to eliminate but at least to diminish the frequency of aircraft entering in upsets and provide recovery from it without exceeding of flight parameters limitations and with minimum discomfort for passengers.

Among these directions of actions there are:

- elaboration of techniques for aircraft recovery from upsets;
- development, elaboration, testing (certification) of adequate ground based training devices for aircrew training on timely recognition of the aircraft entering in upset and probable stall, and also on correct recovery actions of crew;
- elaboration and introduction in the programs of civil aircraft crews periodical training (both ground based and flight) of essential additions which should be directed on training of crews on correct recovery actions;
- development of the System of Information Support of Crew (SISC) advising the crew when aircraft is close to enter in upset conditions. The main task of this system is a prevention of aircraft entering in upsets and semiautomatic or automatic recovery in case of entering.

The choice of direction of research on the problem considered is defined by the specialization of organization working in aviation area. Thus with the aim of development, elaboration and testing (certification) of adequate ground based training devices for aircrew training on timely recognition of the aircraft entering in upset and probable stall, and also on correct recovery actions of crew there was organized under the European 7-th Frame Program a consortium of the Project "SUPRA" – Simulation of UPset Recovery in Aviation. The objective of the SUPRA Project was to develop a new flight simulation concept and prototypical tools for pilot training in recognition of and recovering from flight upsets conditions. In the frame of the Project the following results were achieved:

- it was developed an extended aerodynamic model for large transport aircraft enabling real time mathematical simulation of large transport aircraft behavior beyond the normal operation flight envelope including different types of stall conditions;
- there were elaborated the motion system drive algorithms for both hexapod-type simulators and centrifuge-base simulators;
- experienced test-pilots proved the applicability of the developed simulation concept for line pilots' training.

As an example of elaboration and introduction in the programs of civil aircraft crews periodical flight training of essential additions we can refer to last year introduction of KLM airline of the aircrew training on upset recovery in two Extra L300 single – engine aerobatic aircraft.

2.2 Expertise of the Gromov Flight Research Institute

Federal state unitary enterprise "Flight research institute named after M.M. Gromov" is specialized in the area of various flight researches including flight safety increase in civil aviation. The institute is located in Moscow region, in the city of Zhukovsky – widely known National Center of Aviation, the place where international air-space salons MAKS take place. The next MAKS-2013 will be held in August next year. Flight research institute has got a huge airfield with relevant infrastructure, a number of flying test-beds on the base of flying vehicles of different types and correspondent services supporting flight research on them including a stuff of test-pilots of high qualification.

Scientific – methodical support of flight tests and research is provided by specialists of different profile.

Specialists of the institute deal with the problems of aircraft occurrence in upset conditions for a number of years. At the beginning this work mainly represented an analysis of the reasons of flight incidents and accidents caused by civil aircraft entering to high angles of attack, stall and spin, spatial orientation loss by aircrew, human factor influence etc. And only after bringing to light of definite common regularities in events sequence resulting in aircraft accidents, the prime cause of these accidents had been classified as aircraft entering in upset. Some years ago the institute initiated flight research of different aspects of the problem of aircraft entering in upsets and recovery, prevention of aircraft entering and so on.

3 Upset Recovery Flight Research

3.1 General Considerations

Upset flight conditions have some special features what should be taken into account during flight research, in particular climbing with high flight path angle is accompanied by dynamic deceleration and pilot should prevent aircraft from entering to high angles of attack. Pilot should be able to control aircraft in stall and spin. During descending when speed of flight quickly grows and the height is lost, the pilot should, in conditions of time limit, level aircraft without exceeding of limitations on maximum flight speed, normal g-load and angle of attack. Naturally, safety of such flight research is also dependent from the right choice of research aircraft.

3.2 Flight Research on General Aviation Aircraft Ilyushin-103

Thus the first stage of flight research on upset recovery techniques elaboration was carried out in the Ilyushin-103 aircraft. Il-103, Fig. 2 – light general purpose aircraft. It’s equipped with piston engine IO-360ES of “Teledyne Continental Motors” company, located in nose part of the fuselage. It’s design layout represents cantilever monoplane of all-metal construction with the wing located under the fuselage, single vertical tail and tricycle landing gear.

Fig. 2. Il-103 aircraft.

Maximum indicated airspeed in clean configuration V_{MO}=340km/h. Allowable normal g-load for clean configuration is in the range of n_z= - 3…+ 6 g which is much wider than the analogous g-load range for big aircraft and correspondingly increases flight research safety.

Flight research on Il-103 aircraft on upset recovery techniques elaboration were conducted both in clean and takeoff/landing configurations. Take-off weight was G=1000…1150 kg in a range of center of gravity positions 20…30% of mean aerodynamic chord and flight altitudes of H=500…2000 m. Totally it were executed 36 flights, with participation of 6 test-pilots. Basing on flight research results piloting techniques were elaborated which provide safe aircraft Il-103 recovery from upsets to horizontal flight. The following types of upset conditions were investigated:

- clean configuration with pitch angles θ = +60°…-40° and bank angles ϕ = ±45°;

- take-off configuration (Flaps position 10°) with pitch angles up to θ = +40° and bank angles ϕ = ±45°;
- landing configuration (Flaps position 20°) with pitch angles up to θ = -40° and bank angles ϕ = ±45°.

Envelope for flight test was chosen to be far from normal flight envelope as it was possible to provide safe recovery without flight limitations exceeding. Some investigated flight points for nose down upsets are presented in Fig. 3 as an example.

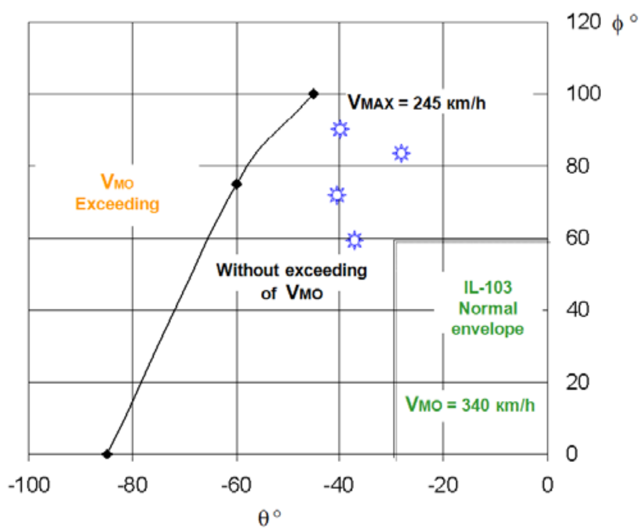

Fig. 3. Flight test envelope for Il-103 aircraft.

It was revealed that for Il-103 aircraft safe recovery to horizontal flight is provided from upsets with positive (nose up) pitch angles up to 60° and bank angles up to ±45°. Aircraft recovery from upsets with positive pitch angles (from "hills") could be performed in two ways:

- by creation of a g-load n_z = 0,7…0,5 g and a bank angle ϕ = ±30°…±60° (most effective, but also the most complicated technique);
- by creation of n_z = 0,5…0,25 g without bank (more simple, but a little less effective method of recovery).

Aircraft recovery from steep climb was initiated at airspeed of V_{IAS}=150…130 km/h. During such maneuvers with pitch angles of θ = 20°…40° the minimum speed during aircraft recovery from steep climb was in the range of $V_{IAS_{min}}$=142…105 km/h, i.e. it was not less than stall speed (V_S = 103 km/h). During recovery from steep climb with pitch angle θ = 60° the minimum speed was $V_{IAS_{min}}$=100…50 km/h, i.e. it was less than stall speed. There were no stalls since g-load value was much less than unit value (about n_z =0,5…0,25 g). However at very small airspeeds, about V_{IAS}=50…70 km/h the accidental sideslip angle increase was observed up to values of β = 15…20° which it was difficult for the pilot to parry by rudder deflection. Therefore at the aircraft recovery from the high positive pitch angles the airspeed decrease less than 100 km/h shouldn't be allowed.

Time spare for pilot to realize the situation and initiate the aircraft recovery from a steep climb at climbs with pitch angles θ = 20° and θ = 30° turns out to be big enough, about 15...30 seconds.

At a recovery from steep climb with pitch angles θ = 40° and θ = 60° the reserve of time turns out to be very small, about 3...5 sec. The last specifies expediency of special aircrew training on civil aircraft recovery from upset conditions.

During Il-103 aircraft entering in upset position in a clean configuration with negative (nose down) pitch angles up to θ = -40° with bank angles up to ϕ = ±45° the safe aircraft recovery in horizontal flight is provided. Aircraft recovery from such dives was performed in the following way: bank angle was eliminated by control stick deflection in roll channel up to zero and then leveling of aircraft was initiated up to horizontal flight by creation of g-load n_z=2,1…2,8 g at airspeeds V_{IAS}=200…220 km/h (for such airspeeds the range of maximum allowable g-loads is $n_{z_{lim}}$=3,2…3,9 g; and maximum exploitation value of g-load is n_z^e = 4,4 g). The airspeed increase during pullouts was equal to 15...50 km/h, the flight altitude loss was of 60...150 m depending on an initial pitch angle.

For take-off configuration (Flaps position 10°) safe recovery of Il-103 aircraft to horizontal flight was provided up to pitch angles of θ = +45° at bank angles of ϕ = ±45°.

For landing configuration (Flaps position 20°) safe recovery of Il-103 aircraft to horizontal flight was provided up to pitch angles of θ = - 40° at bank angles of ϕ = ± 45°.

Of course it is impossible to extend fully the results of these researches on transport aircraft, because Il-103 is related to aircraft of another class, has engine with two-blade propeller, features high allowable g-loads etc. But upset recovery techniques elaborated in flight research in Il-103 aircraft were taken into account during development of flight research technique for non-maneuverable aircraft.

3.3 Flight Research on Tu-154M flying test-bed

Further flight researches on non-maneuverable aircraft upset recovery techniques elaboration were conducted on Flying Test-Bed (FTB) created in the Gromov flight research institute on the bases of Tupolev-154M №85317 aircraft.

3.3.1 Description of Tu-154M FTB

Tu-154M aircraft (see Fig. 4.) is intended for airlines up to 5000 km long. It has got three bypath turbofan engines D-30KU-154, located in rear part of the fuselage. It's design layout represents cantilever monoplane of all-metal construction with swept wing located under fuselage, T-tail empennage and tricycle landing gear.

Fig. 4. Tu-154 №85317 FTB aircraft.

Peculiarities of aerodynamic layout provide the presence of deep stall and flat spin modes in the area of supercritical angles of attack.

Allowable normal g-load range for clean configuration is n_z =0…2,2 g. Maximum indicated airspeed for clean configuration - V_{MO}=600 km/h.

For the purpose of flying test-bed creation the serial Tu-154M aircraft was equipped with:

- analog triple redundant fly-by-wire flight control system in pitch, roll and yaw channels;
- digital fly-by-wire flight control system in pitch, roll and yaw channels;
- digital auto throttle;
- variable stability and controllability system;
- pilot flight deck instruments on the basis of color liquid crystal displays;
- satellite navigation systems;
- equipment for atmosphere parameters measurements;
- emergency escape system;
- onboard instrumentation system;
- other experimental system to support flying test-bed operation.

Cockpit of serial Tu-154M aircraft was modernized (see Fig. 5).

Fig. 5. Tu-154M FTB cockpit layout.

Captain is right-hand pilot, who has basic mechanical flight control system and pilot instruments.

Left-hand pilot's station instead of traditional column is equipped (depending on research purposes) with experimental pilot controllers: mini-wheel, central stick, left and right sidesticks, experimental throttle levers.

FTB provides simulation of dynamics and flight control system (including algorithms for control of aircraft and engines, pilot hand controllers, formats of flight parameters representation on head-down and head-up displays and so on) of non-maneuverable aircraft of any type with the aim of:

- research of digital fly-by-wire flight control systems (DFBW) of flying vehicle (FV) and engines;
- development of exploitation techniques for aircraft noise on the ground abatement;
- development of expert systems for aircrew support in different flight modes including critical ones;
- research of techniques for satellite navigation systems integration in manual flight control loop of FVs;
- evaluation of new FV pilot hand controllers, implemented in highly augmented DFBWs;
- investigation of formats of flight parameters presentation on head-down and head-up displays;
- development of criteria and requirements in the area of FV flight dynamics and control;
- research on human factors aspects and on pilot psycho-physiological workload;

Besides FTB is intended for research on:

- satellite and inertial navigation systems integration;
- aviation influence on environment.

3.3.2 Math simulation of Tu-154M FTB dynamics during upset recovery

Initially the math simulation on Tu-154M №85317 FTB dynamics math model was performed to increase flight research safety. To control FTB math model in upsets at these simulations the special autopilot math model was implemented, having gain values chosen to simulate flight control surfaces deflections by the pilot. FTB flight was simulated in all configurations: clean, take-off and landing. Aircraft entering in upset and recovery was carried out with prescribed constant value of normal g-load achievable in the limits of available elevator deflections and without exceeding of allowable limits of g-load n_z=0…2,0 g and AOA.

In the longitudinal channel for autopilot it was used the usual integral control law for stabilization of a preset value of a normal g-load with introduction of its gradient change for imitation of time for column deflection by the pilot. During an entering/recovering from upset position the prescribed value of a normal g-load was limited by the following:

- The value of maximum lift force coefficient C_l in the current flight conditions. During the simulation this given value corresponded to adjustments of operation of the regular high angle of attack/g-load warning system.
- G-load limitations according to flight manual.

In the aileron control channel it was used the static control law for stabilization of the given bank angle with introduction of its gradient change for imitation of time for wheel rotation by the pilot.

Inclusion of the autopilot signals in pitch and roll channels was carried out separately, according to sequence diagram, depending on a type of spatial position of the aircraft.

During upsets in climbing without bank angle the recovery techniques both without aircraft banking and with bank angle utilization were considered. In case of initial bank angle presence the aircraft recovery from upset in climb to horizontal flight was performed either with keeping initial bank angle value or with it increase.

During aircraft recovery from upsets in diving also the cases with and without initial bank angle were simulated.

Two variants of autopilot algorithms were applied for recovery from upset in diving at bank angle presence.

Autopilot of the first type initially recovered FTB model in straightforward flight with diving and elevator inputs to bring aircraft to horizontal flight were applied only when bank angle have reached the limits $|\phi| \leq 5°$.

Autopilot of the second type simultaneously recovered aircraft from bank and diving.

At the first stage of simulation the real initial airspeeds of the Tu-154M FTB aircraft in upset position were determined. For determination of the minimal airspeeds at negative flight path angles the entering of the aircraft in descend from horizontal flight on the minimal speed by full forward column deflection was simulated at the minimal engines operation modes. For determination of the maximal airspeeds at positive flight path angles the entering of the aircraft in climb from horizontal flight at maximal speed was simulated by the creation of a g-load $n_{z_{max}}$=2 g at engines maximal operation modes. Simulation was carried out in the whole range of heights of flight and for all aircraft configurations.

Basing on simulation results the marginal areas of aircraft attitudes from which safe recovery is possible were identified. An example of such area is presented in Fig. 6. as a dependence of minimum allowable flight path angle from indicated airspeed at the beginning of upset recovery for clean configuration at different altitudes.

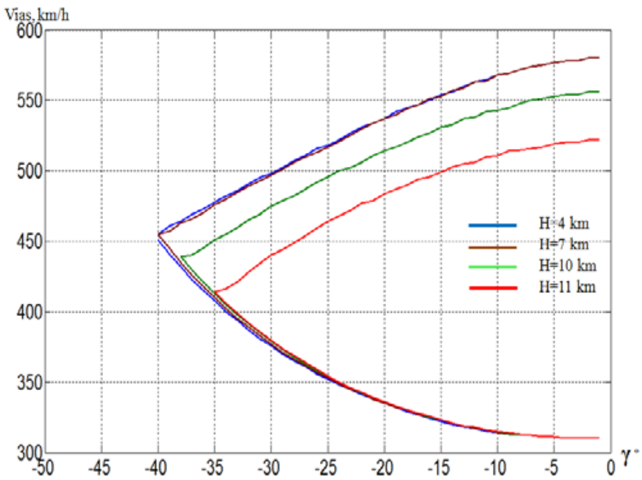

Fig. 6. Dependence of minimum allowable flight path angle from indicated airspeed at the beginning of upset recovery for different altitudes.

During calculations of the curves presented in Fig. 6. the recovery from rectilinear descent to horizontal flight was provided by autopilot math model with creation of g-load not more than n_z=2g without exceeding limitations for airspeed (Mach number).

There were also determined the dependences of altitude and airspeed variations during aircraft upset recovery from initial flight conditions (aircraft configuration, altitude, indicated airspeed, pitch and bank angles) and g-load value at recovery. Efficiency of engine operation mode change during upset recovery, airspeed brakes and landing gears deployment, etc. was also investigated.

3.3.3 Results of flight research on Tu-154M

Flight research on Tu-154M №85317 FTB on transport aircraft upset recovery techniques elaboration were conducted after test-pilots of the Gromov flight research institute have been trained in ground-based simulator. It was demonstrated that safe recovery of Tu-154M FTB aircraft to horizontal flight is provided in the range of pitch angles θ = -44°…+53° in clean configuration, θ = -40°…+46° in take-off configuration and θ = -34°…+37° in landing configuration without exceeding of flight manual limits for g-load, AOA and airspeed (Mach number).

At the beginning of flight tests the Tu-154M FTB recovery from upsets in climbing without bank was carried out only by g-load creation.

Then flight research trials were conducted with simultaneous creation of g-load and bank angle up to $|\phi| \approx 80°$ in clean configuration and $|\phi| \approx 60°$ in take-off and landing configurations. Analysis of flight tests data and pilot comments have revealed that creation of bank angle of values $|\phi| \leq 60°$ for clean configuration has no significant influence on aircraft deceleration rate decrease. Meanwhile creation of big bank angles simultaneously with recovery from high pitch angles requires definite skills and relevant pilot training. Bank angles utilization is not effective for take-off and landing configurations because at roll and pitch rates available the aircraft transition to descent occurs earlier then high bank angles will be achieved and it again requires definite pilot skills. Thus aircraft recovery from upset in climb should be performed first of all by pitch angle diminishing with bank angle monitoring and control.

Engine's thrust increase is effective for recovery from nose up upsets with pitch angles of $\theta \geq$ 30°.

Tu-154M FTB recovery from upset in diving initially also was carried out with almost zero bank angle. For clean configuration at bank angles of $|\phi| \leq 45°$ (in take-off and landing configurations at $|\phi| \leq 30°$) the aircraft recovery from diving could be performed simultaneously with bank angle elimination. In case of big bank angles it is necessary initially to deflect ailerons to start bank angle elimination and then to deflect elevator to recover from descent. Also it worth to use airspeed brakes (middle interceptors). Engine thrust setting to “Idle” is efficient at pitch angles $\theta \leq -20°$.

4 System of Information Support of Crew

One of possible means for aircraft entering in upsets prevention is development of the System of Information Support of Crew (SISC) in critical flight situations. Such system should perform a prognosis of flight parameters change and in case of possible exceeding of limit values to generate and provide to aircrew the recommendations on necessary actions.

SISC elaboration was based first of all on the margins of flight envelope in coordinates [θ - ϕ] from which it is possible to recover the Tu-154M FTB aircraft from upset without exceeding of limitations on airspeed, g-load and angle of attack. These borders were obtained during math simulation trials described above. Next, optimum piloting techniques for aircraft recovery from upset developed in math and ground based simulations were utilized to determine, what are the maximal values of flight speed and altitude losses at an optimum recovery from upset. Finally the dependencies of boundary values (maximum and minimum) of indicated airspeed V_{IAS_b} were determined on the basis of math simulation as functions:

$$V_{IAS_b} = F(V_{IAS}, H, \theta, \phi, G, Flaps) \qquad (1)$$

of indicated airspeed, altitude, bank and pitch angles, aircraft weight and configuration. These dependencies were implemented in Tu-154M FTB onboard computer along with algorithms for aircraft speed variations prognosis and algorithms for commands to aircrew generation. At prognosis of airspeed going out of boundary values and depending from aircraft attitude the relevant commands on bank angle diminishing, pitch angle increase or decrease, engines’ operation mode change were displayed on pilot head-down display. The Gromov flight research institute test-pilots participated in flight research positively evaluated these algorithms operation.

5 Conclusions

For the first time in Russia the flight research on real upset recovery of heavy transport aircraft were conducted and relevant recovery piloting techniques were elaborated.

The objective data obtained during upset recovery flight research on aircraft of various aerodynamic layout could be used for:

- Development of advanced flight simulators suitable for transport aircraft aircrew training in upset recovery piloting techniques.
- Elaboration of the Systems of Information Support of Crew in critical situations.

Recovery techniques from upset conditions related with unusual aircraft attitudes were elaborated.

First version of SISC algorithms was tested in flight and received positive test-pilots evaluations.

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