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IN - FLIGHT SIMULATOR FOR EVALUATION OF PERSPECTIVE CONTROL CONCEPTS OF THE TRANSPORT AIRPLANE

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Abstract

Flight Research Institute is conducting researches using the in-flight simulator based on the Tu-154M transport aircraft. It was designed for a complex investigation of advanced control concepts and as a result of it optimization of the "pilot-airplane" system parameters. The simulator is equipped with sidestick controllers, a mini-wheel, digital flight control system and head-up displays. Besides it is possible to control the simulator using the ground-based computer included into the telemetry airplane-ground-air plane control link.

Every experimental system as well as the simulator dynamic one has variable-in-flight characterictics.

The paper discusses the ideology of experimental system realization on the simulator. There are presented certain results of optimization and comparison of parameters of mini-controllers of different types and determination of the transport aircraft handling qualities depending on the type of the controller. Also there are given results of using mini-controllers together with advanced highly augmented control laws for transport aircraft. For the flight testing there were determined in accordance with the aircraft control laws optimum formats of flight navigational data presentation.

1. Introduction

The flight safety and control quality of an aircraft are to a considerable extent determined by the characteristics of those systems which form up the control loop and with which the pilot is directly interacting. They include a flight-navigational data presentation system, controllers and control system or control laws to be more exact which together with the airframe characteristics determine the dynamics of a modern aircraft.

Recent improvements of the onboard equipment resulted in introducing on civil airplanes colour electronic displays for flight-navigational data presentation, sidesticks and mini-controllers. The use of advanced digital control laws provided new handling characteristics of an aircraft and made it possible to automate certain control functions and to combine manual and automatic control modes. These means allow to get the most effective "man-machine" interface, though it is necessary while determining the optimum "man-machine" system characteristics to evaluate a great number of parameters as well as to take into account subjective factors of real flight. There is required a complex evaluation of such factors as control precision, pilot workload, his fatigue, the adaptation level etc., with taking into consideration a possible variation of the pilot characteristics both in normal flight and in failure one. All of the mentioned problems can be solved on the in-flight simulator (FS) allowing a flexible and fast varying of characterisics of the control loop and aircraft dynamics in flight in order to directly compare different characteristic variants and determine the most effective combination of them.

2. In-flight simulator description

To conduct flight research of new control and dynamics concepts the Flight Research Institute has developed FS based on the Tu-154M three-engined medium-range aircraft (see Fig.1). Concretly speaking FS is designed to evaluate advanced controls and highly augmented control laws and to work out a concept of flight-navigational data presentation on electronic displays for new generation civil aircraft. The left seat in the cabin is a research one (see Fig.2 and Fig.4).

The conventional wheel and mechanical links have been removed from that seat. It is equipped with fittings for installation of the left and right sidesticks of different types and also of a centre mini-wheel. Conventional panel instrumentation is replaced by a colour electronic display and head - up flight-navigational data display. FS is controlled by a digital fly-by-wire (FBW) system. All experimental systems of the control loop as well as FS dynamics have variable characteristics.

There have been investigated sidesticks of different forms which provide pitch, bank and, if neccessary, yaw control. All the stick controllers have force transducers. The sidestick parameters (location, pivot point, force-displacement) are variable.
The stick construction allows to change the stick from a force controller to a controller requiring up to ±5cm displacement. A special block makes it possible to change the control sensitivity in flight. The miniwheel provides similar functions. FS is controlled by the left-seat pilot by means of a digital FBW system (see Fig.3). The on-board computer has a high-level language and it can be in real time reprogrammed in flight. The computer provides different aircraft and engine control laws for manual and automatic control. It is possible to change the FS handling qualities in flight in order to evaluate and optimize them and

also to simulate advanced airplane dynamics. Simpler control laws can be realized with the help of a triple-redundant analog fly-by-wire system. Besides, the onboard telemetry up and down links and the ground-based computer provide FA real time advanced control laws. The time delay does not exceed 0,05 sec. A number of auxiliary ground-based computers provide data analysis during flights. Experimental FBW systems (using both on-board and ground-based computers) are connected to conventional actuators of the Tu-154M aircraft. When FBW is operated mechanical control system and the right column follows the surface position. This increases flight safety and provides smooth transition to conventional control in case of a FBW failure.

A colour electronic head-down display and also head-up one are fed from the on-board digital mini-computer which generates in real time graphic imagery. A macrolanguage specially developed is used for a quick reprogramming of the computer. This allows to present to the pilot in flight different formats of flight-navigational data to be directly compared or corrected so that the optimum variant could be determined.
Let us discuss some of the results received.

3. Flight research results

We know about successful flights of the A-320 aircraft with a sidestick and positive experience of the sidestick research at our Institute. It was considered necessary to carry out additional research of the sidestick together with a digital highly augmented control system in order to confirm a high degree of reliability and perfect handling quality. It's necessary to carry out a combined optimization of controller parameters and aircraft handling qualities taking into account human factor. The main problems discussed are as follows:

- the influence of the sidestick type and location on pilot ergonomic rating;
- optimum force-displacement characteristics of the sidestick and handling qualities of the aircraft with a sidestick installed;
- pilot workload in flights including long duration ones;
- quickness of pilot adaptation to the sidestick and some other problems.

It was of special interest a possibility of flying with the left sidestick both in normal conditions and failure ones taking into account different qualification levels of pilots.

Thirty test-pilots of different flying experience, qualification and age took part in the flight research of the sidestick to ensure objective results. Also a group of test pilots of long flight experience with maneuverable aircraft participated in the tests. The research was conducted in different weather conditions and flight regimes including visual and instrument approaches and landings.

Testing sidesticks of different forms and evaluations made by a great majority of test pilots helped to reveal the advantage of the sidestick shown in Fig.5.
In accordance with the objective data and the pilot ratings a sidestick is convenient for pitch and bank control, but adding of yaw control disturbs the established control manner and makes control difficult for the pilot in an emergency.

The optimum location of the sidestick is the one on the arm-rest with necessary regulation of its position in height and along the arm-rest. The longitudinal axis orientation is 28 deg. forward and 12-15 deg inside the cabin.

The convenient pivot point location is at the base of the stick. It provides ease and precision of control.

The flight research showed that for transport aircraft the sidestick with the medium displacement range (approximately $\pm 2,5$ - $\pm 3,0$ cm from the stick mid-point) is most acceptable. For the main part of the flight envelope for pilots of different physical abilities the amount of stick force required per unit of stick displacement is 0,9-1,1 kg/cm in pitch and 0,7-0,9 kg/cm in bank control (see Fig.6). Bank control forces are asymmetric. The breakouts of $\pm 0,4$ kg and $\pm 0,3$ kg for pitch and bank correspondingly prevent any cross-coupling of these channels and provide the required control precision. It is interesting to note that separate pilots from the fighter-pilot group gave the same evaluations when the sidestick was practically immovable.

Before the flight testing some of the pilots were rather sceptical about the left sidestick. However the results showed that in this case reliable and effective control can be achieved for all regimes including approaches and landings. The precision of the sidestick control and conventional one was practically equal.

Dynamic characteristics of the closed pilot-aircraft loop with different controllers were studied. For that purpose a quasi-random signal with the appropriate spectrum was sent to the surface actuators by the ground computer or on-board one. The pilot's task was to stabilize the aircraft in these conditions. A combined analysis of the input and output data allowed to determine the loop dynamic response for different type of controllers. The frequency characteristics of pilot control show that the sidestick provides less time delays in the loop compared with the conventional column. The frequency characteristics of pilot in the sidestick control loop revealed his differentiating function which speaks of his prognostic ability (see Fig.7).

It is necessary to point out that pilots almost irrespective of their qualification level and flight experience beco-

me quickly adapted to the sidestick controller.
As a rule a 1-1,5 hour flight and three to four approaches were quite sufficient for the pilot to acquire positive skills of piloting the airplane with a sidestick in normal conditions.

On the whole the optimum pilot workload and sidestick force-displacement parameters determined in the course of flight testing provided for the comfort of the airplane handling. Flights of sufficiently long duration (three to four hours) made by the airplane with the sidestick control (conditions similar to the automatic control system failure) showed that flying such a plane according to the pilots causes much less fatigue than when using the control wheel. The flight results also showed that a choice of sidestick parameters must be made most thoroughly for flights in turbulence and to prevent disturbances in the control loop and pilot induced oscillation.

The mini-controller benefits (of the sidestick, in particular) are revealed to a greater extent when the controllers are integrated with the highly augmented control system. The existing digital equipment allows to implement a flexible division of the manual and automatic control functions to best consider human factor.

There was studied a digital control law using pitch, g-loads and other flight parameters in positional and integral feedback (see Fig. 8). Such a law provides a number of important features for the airplane dynamics which affect the method and quality of piloting:

1. Neutral stability of aircraft when speed is changing. In this case the controller position is not an additional indication of the current flight speed to the pilot. But in case of a small mini-controller displacement this conventional characteristic loses its significance. All the pilots were positive in evaluating this feature noting that flying the plane became easier when the flight speed changed and that there was no need for control force trimming.

2. Possibility of setting rather simple algorythmic limitations to critical flight parameters (angle of attack, g-loads, maximum speed etc.). This prevents exceeding of limitations for short-period parameters even when mini-controller is fully deflected which is possible in stress conditions. If the limiting speed (maximum or minimum) is exceeded the surfaces are automatically set (for a nose up or down correspondingly) keeping the aircraft within the speed limits. According to the pilots this concept does not violate the usual control manner, but it makes piloting simpler and is adopted easily by the crew. It allows pilots to feel more sure of themselves and pay more attention to checking the systems state and observing the outside scene, which increases flight safety especially during maneuvering in the airport zone.

3. Increased control precision. The integrated system is characterized by an increased aircraft stability on the flight path. This is particularly important for precision control regimes, for example, approach.
The flight test results showed that the use of the control law with integral feedback considerably increases the control precision and reduces the pilot workload. (see Fig.9 and 10).

Of importance is also the concept of transition from the manual to automatic control mode and visa versa. On FS there was positively evaluated a concept providing a transition to the autopilot control when no force is applied to the sidestick and a return to the manual control when the sidestick force is applied. The corresponding delay time of approximately 1,0 sec and 0,1 sec prevents any random autopilot engagement and its quick disengagement by the pilot. The maximum values of the autopilot engagement/disengagement forces are taken equal to the sidestick breakout forces. The results of the objective data analysis and pilots opinions speak of a considerable reduction of pilot worload:
the frequency of the pilot control inputs decreases and the pilot pays more attention to monitoring the aircraft flight trajectory, equipment operation, etc. At the same time control precision noticeably increases. In pilots' opinion this type of control must be the main control mode for civil airplanes.

During flights there were evaluated optimum handling qualities ranges of transport aircraft equipped with the sidestick controller and highly augmented system. As a result of averaging the pilots' Cooper-Harper ratings there were determined optimum sidestick force amounts per unit of control response (see Fig.11).

In accordance with the concept of advanced control laws discussed the pilots' main flight task is to perform attitude and navigation control, while the tasks of flight parameter stabilization, keeping within limitations etc. must be performed automatically. This concept must be realized in the logic of flight-navigational data presentation on displays for the pilot. Proceeding from this it is most natural to use the information of the vector velocity. It is worthwhile using graphics providing perspective 3-D imagery. This allows to make use of the pilots intuitive attitude control ability in the control process and make closer graphic data perception on head-down and head-up displays when the symbols of the latter are "superimposed" on the outside view. At present there are no formal methods of optimizing graphic formats of the flight-navigational data presentation on displays. In flight conditions when there are many contradicting factors acting upon pilots it is rather difficult to determine any measurable connection between many of the elements of the graphic data presentation and the pilot workload. Thus the optimum format is determined by iteration, and for this participation of a great number of pilots and their experience are necessary as well as comparison of their evaluations of different formats. On-ground simulator and FS research results show that the optimum format provides the required quality of control and landing within the Cat III conditions. The format also provides for additional future data visualization of predicted flight paths and the touchdown. In order to compare different formats of flight-navigational data presentation on displays there are used pilot ratings, their answers in the questionnaire, objective data of the control precision and ergonomic measures of the pilot workload.

Conclusions

1. The in-flight simulator with in-flight variation of the controller type and characteristics, control laws, flight-navigational information presentation systems and dynamics is a highly effective means of optimizing the "pilot-aircraft" system in investigating new control concepts for transport aircraft.

2. Tests conducted on the in-flight simulator confirmed a general tendency towards realizing on transport aircraft the control concept presupposing the use of:

- mini-controllers (sidesticks, in particular);
- highly augmented control laws providing direct control of flight trajectory parameters and flexible division of the manual and automatic control functions;
- presentation on head-up and head-down displays of flight - navigational information the graphic imagery of which is in conformity with control laws.

Fig.1. GENERAL VIEW OF THE Tu-154M IN-FLIGHT SIMULATOR

THE Tu-154M IN-FLIGHT SIMULATOR

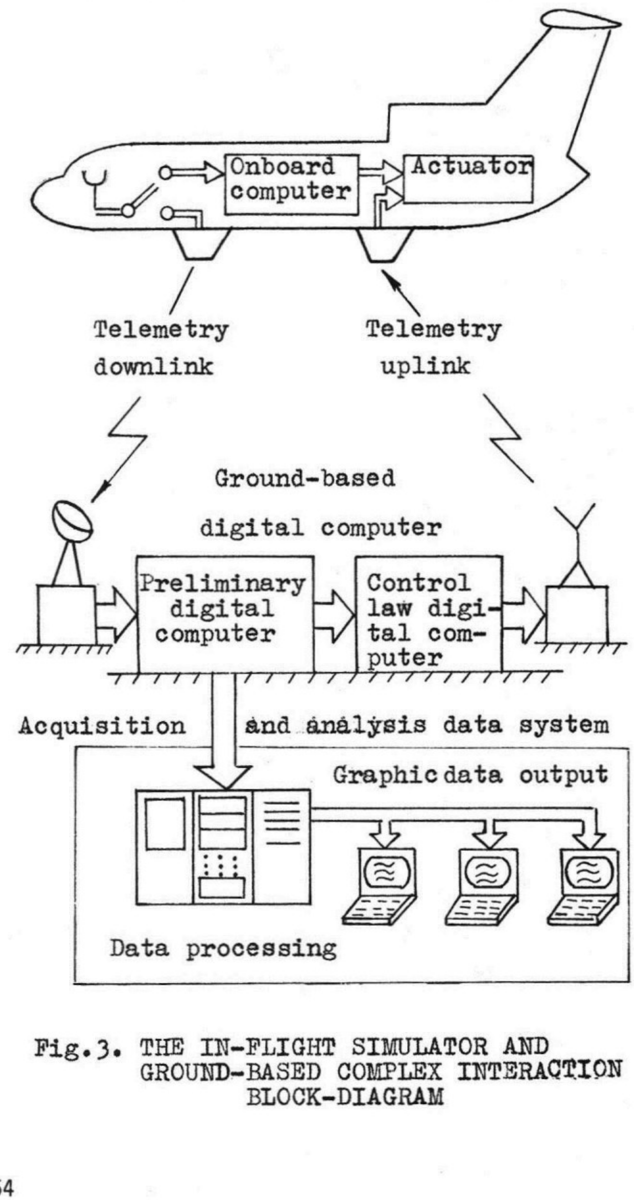

Fig.3. THE IN-FLIGHT SIMULATOR AND GROUND-BASED COMPLEX INTERACTION BLOCK-DIAGRAM

Fig.2. THE Tu-154M IN-FLIGHT SIMULATOR COCKPIT

Fig.4. THE LEFT EXPERIMENTAL SEAT OF THE Tu-154M IN-FLIGHT SIMULATOR

Fig.5. TYPES OF THE SIDESTICK CONTROLLERS INVESTIGATED

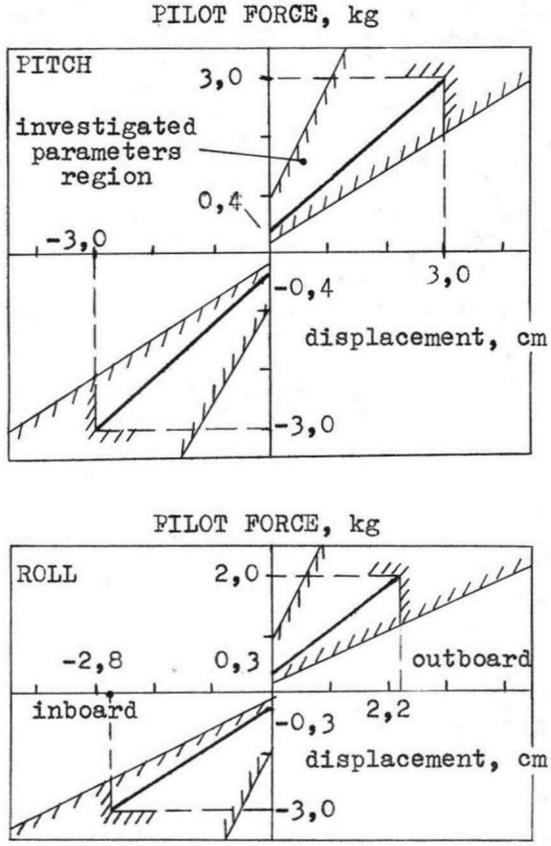

Fig.6. FORCE-DISPLACEMENT CHARACTERISTICS OF THE SIDESTICK CONTROLLER

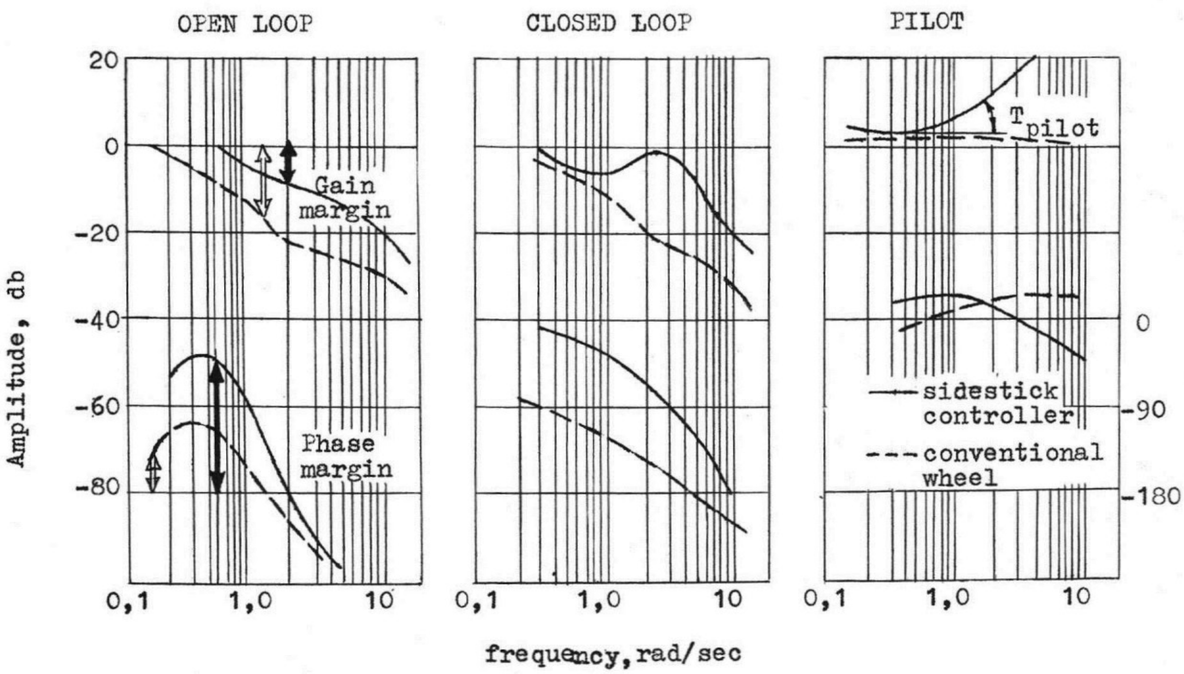

Fig.7.FREQUENCY CHARACTERISTICS OF PILOT-AIRCRAFT SYSTEM

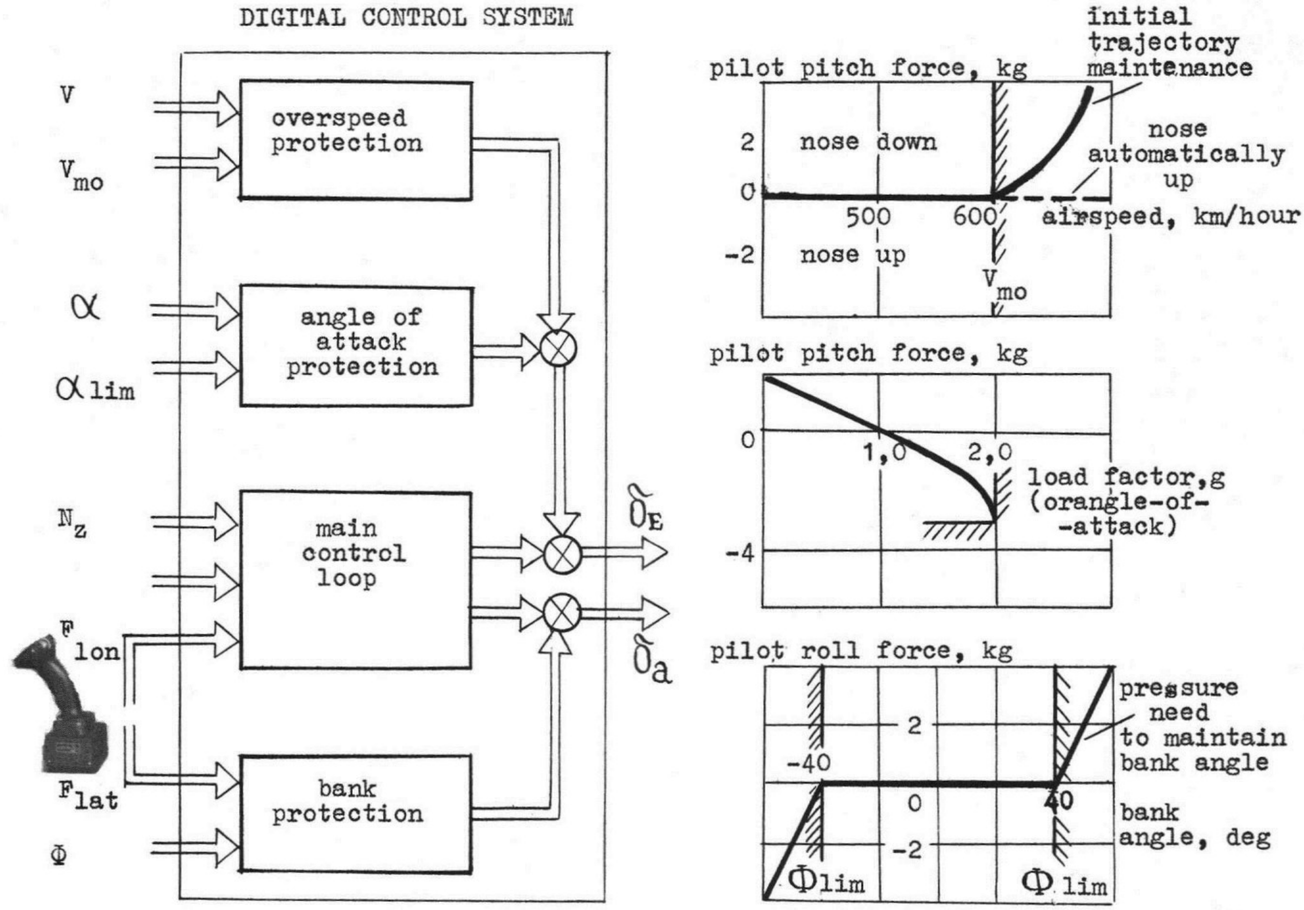

Fig. 8. BLOCK-DIAGRAM: ONE OF THE IN-FLIGHT SIMULATOR CONTROL LAWS

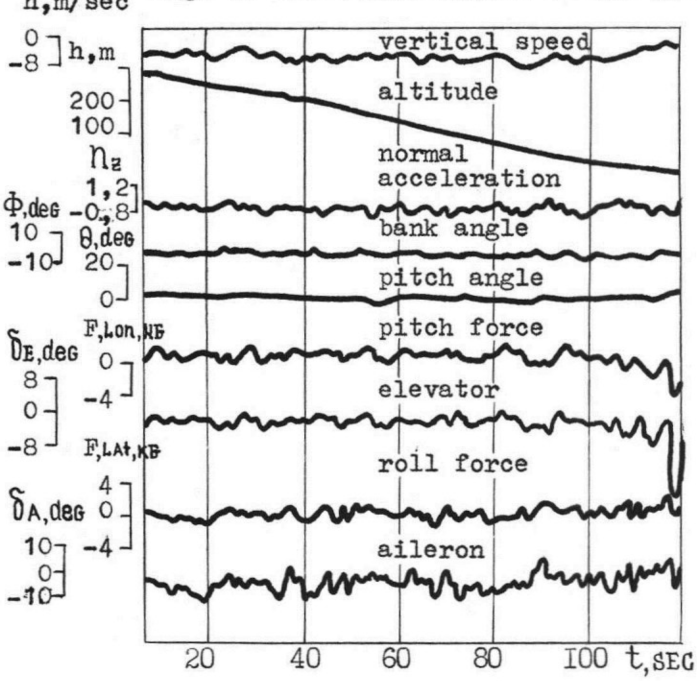

Fig.9. LANDING APPROACH TIME HISTORIES.
CONVENTIONAL CONTROL LAW

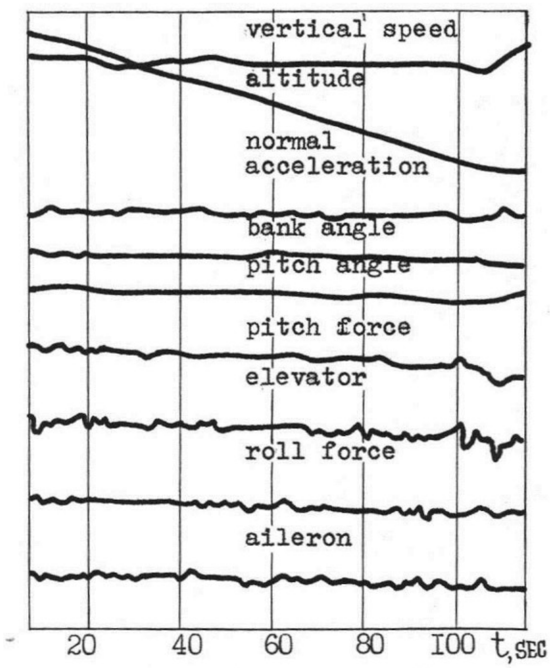

Fig.10. LANDING APPROACH TIME HISTORIES.
ADVANCED CONTROL LAW

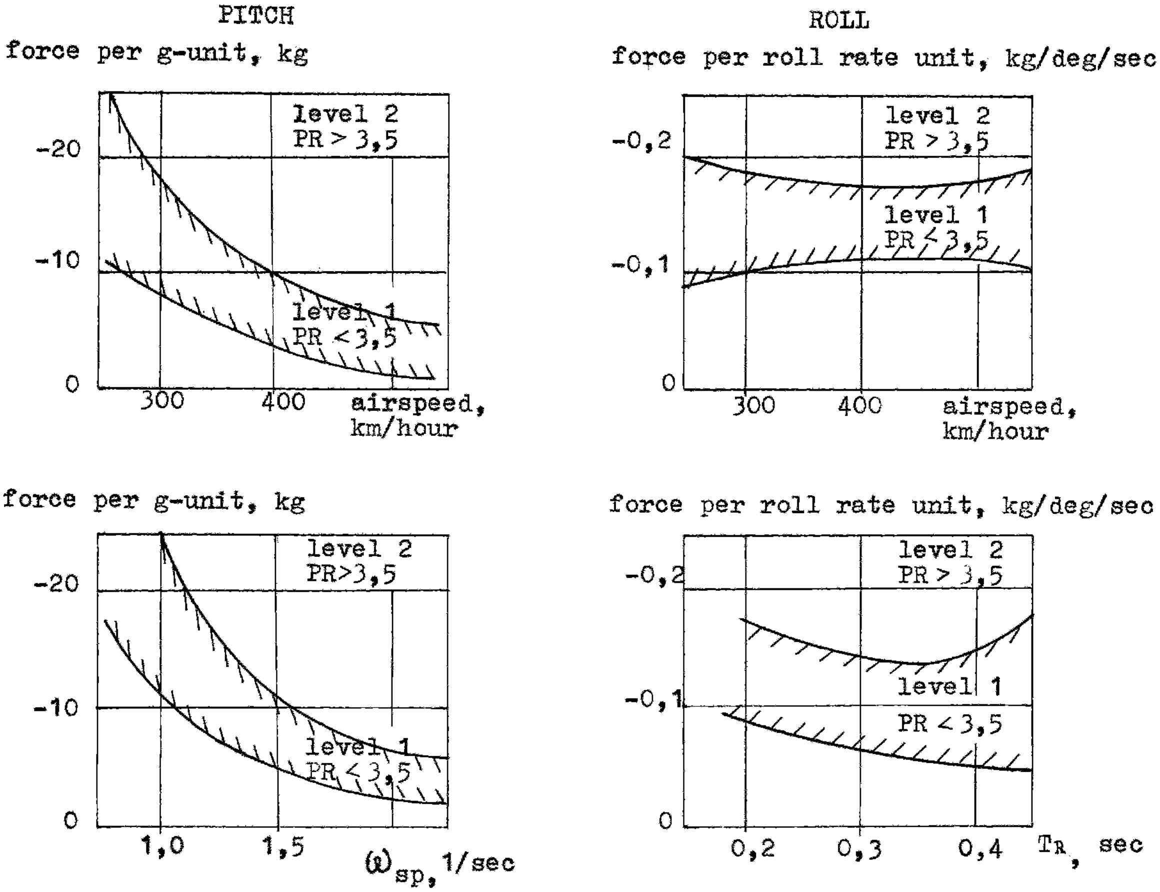

Fig.11. OPTIMAL HANDLING QUALITIES OF IN-FLIGHT SIMULATOR WITH SIDESTICK AND HIGHLY AUGMENTED CONTROL SYSTEM