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SOME RESULTS OF THE APC-1P DIGITAL AUTOPILOT FLIGHT TESTS

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This paper presents methodology and results of the digital autopilot flight tests. The structure of autopilot, methods of experiment applied in tests on four prototypes with PZL M20 Mewa are shown. Ways of data analysis and some obtained results are discussed.

1. Introduction

It is well known that automatic flight control is a subject which has strongly influenced the progress in aviation occurring last years. It is one of the results of the computer revolution which gave a lot of new possibilities in control systems designing.

In accordance with new trends and real needs of Polish aviation, the first digital autopilot, was designed and made at the Technical University in Rzeszów, Poland (Bociek et al., 1989a,b)[1]. Prototypes were investigated in laboratory conditions and the results were found to be practical and successful. In the subsequent step, most decisive about the device reliability, the autopilot was subjected to flight tests to meet the FAR 23 requirements (issued by Federal Aviation Administration, USA) which it passed and thus obtained national certification.

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[1]see also Tomczyk A. (red), Projekt, wykonanie i badania cyfrowego autopilota do samolotów lekkich, Politechnika Rzeszowska, Raporty nr U-1801 i U-2075, 1987-90 (unpublished)

2. Description of the autopilot

2.1. General description

From the control theory point of view, the flight control system may be shown as multi-input/multi-output control system (Fig.1). The system has a hierarchic structure in which three levels of control are distinguished

- attitude stabilization level (stabilization loop)
- trajectory stabilization level (trajectory control loop)
- navigation control level (navigation loop).

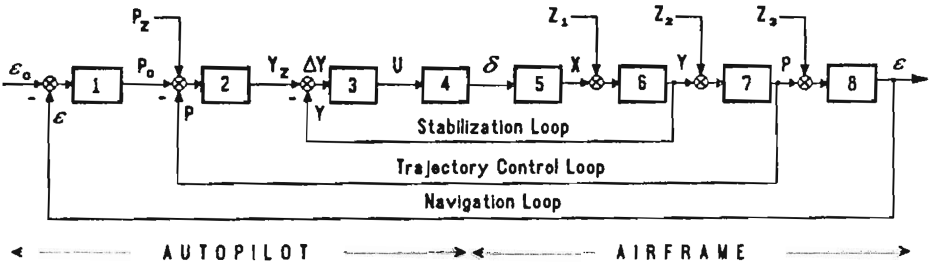

Fig. 1. Block-diagram of the automatic flight control system; 1 – navigation module of the autopilot, 2 – trajectory control module of the autopilot, 3 – attitude stabilization module of the autopilot, 4 – actuators, which deflect the aircraft aerodynamic control surfaces, 5 – aircraft (multi-input/multi-output object), 6 – attitude reference system, 7 – trajectory parameters measurement instruments, 8 – navigation on-board equipment

The airframe, on-board instruments and the control system are described by the following variables and parameters

$\boldsymbol{X}$ – state vector; typical $\boldsymbol{X} = [\boldsymbol{X}_P, \boldsymbol{X}_R]^\top$

$\boldsymbol{X}_P = [u, \alpha, q, \vartheta, h]^\top$ $\qquad$ $\boldsymbol{X}_R = [\beta, p, \varphi, r, \psi]^\top$

u – incremental velocity [m/s]

α, β – incremental angle of attack and sideslip angle [rd]

q, p, r – incremental pitch, roll and yaw rates [rd/s]

ϑ, φ, ψ – incremental pitch, roll and yaw angles [rd]

h – incremental altitude [m]

$\boldsymbol{Y}$ – output vector; typical $\boldsymbol{Y} = [\vartheta, q, \varphi, p]^\top$

$\boldsymbol{Y}_z$ – calculated output vector

$\boldsymbol{P}$ – flight parameters vector; typical $\boldsymbol{P} = [\psi, h, V]^{\mathrm{T}}$
V – air-speed [m/s]
$\boldsymbol{P}_z$ – vector of the command flight parameters
$\boldsymbol{P}_o$ – vector of the calculated flight parameters
$\boldsymbol{U}$ – control vector
$\boldsymbol{\delta}$ – vector of the surfaces deflection
typical $\boldsymbol{\delta} = [\delta_E, \delta_A, \delta_R, \delta_T]^{\mathrm{T}}$
δ_E – elevator deflection angle [rd]
δ_A – aileron deflection angle [rd]
δ_R – rudder deflection angle [rd]
δ_T – thrust (power) control lever deflection angle [rd]
$\boldsymbol{\varepsilon}$ – vector of the navigation receivers signals
typical $\boldsymbol{\varepsilon} = [\varepsilon_V, \varepsilon_L, \varepsilon_G]$
ε_V – VOR[1] receiver signal (radial deflection) [rd]
ε_L – localizer signal (ILS[2] approach) [rd]
ε_G – glide slope signal (ILS approach) [rd]
Z_i – atmosphere turbulence influence, radio transmition disturbances, and measurement errors.

Mathematical models of aircraft, instruments and the control system were used to establish the autopilot control laws. These control laws were verified by computer simulation to account for effects of discretization and quantization, 8-bit microprocessor arithmetics, digital recursive filtering of data. and nonlinearities introduced into the control system.

The APC-1 autopilot was designed according to the main Cat. I ICAO automatic flight control system requirements, as follows

- high quality steering and disturbance resistance
- high level of steering process automatization
- high reliability (the fail-safe system)
- limited possibility of the dangerous situation appearance, and signaling them when occur
- autopilot disconnecting facility and operating comfort
- possibilities of aircraft manual steering, even in case of autopilot malfunction.

[1]VOR – Very-high-frequency Omnidirectional Radio-beacon
[2]ILS – Instrument Landing System

The autopilot can be regarded as a specialized microprocessor controller. From a signal processing point of view, electric signals from on-board instruments by means of specialized interfaces and an A/D converter are sent to Z80 8-bit microprocessor, where they are transformed into control signals. The power amplification control signals drive electric servos which deflect the aircraft aerodynamic control surfaces.

From a user's point of view the autopilot provides several functions typical for civil aircraft

- pitch and roll attitude stabilization and control
- altitude stabilization
- stabilization of the selected heading
- VOR navigation (intercepting and tracking VOR radials)
- ILS approach (localizer (LOC) and glide slope (GS) beams intercepting and tracking, and localizer back course mode).

Two basic modes of the autopilot are available

- automatic flight control, it simply means basic autopilot functions
- flight director mode.

Design, production and testing were made according to the international requirements: FAR 23 Regulations, R.T.C.A. DO160B, TSO C9c and AS402 A Norms.

2.2. The hardware

The autopilot was made from commercially available components. The digital controller was based on Z80 microprocessor. The first version was designated to be built on board of the PZL M-20 "Mewa" twin-engine aircraft.

The set of the autopilot includes (see block-diagram in Fig.2)

- main processing unit (flight computer)
- pilot's selector panel
- servos deflecting ailerons, elevator, and elevator trimmer
- servo controllers (drivers)
- optical flight director indicator (optionally)

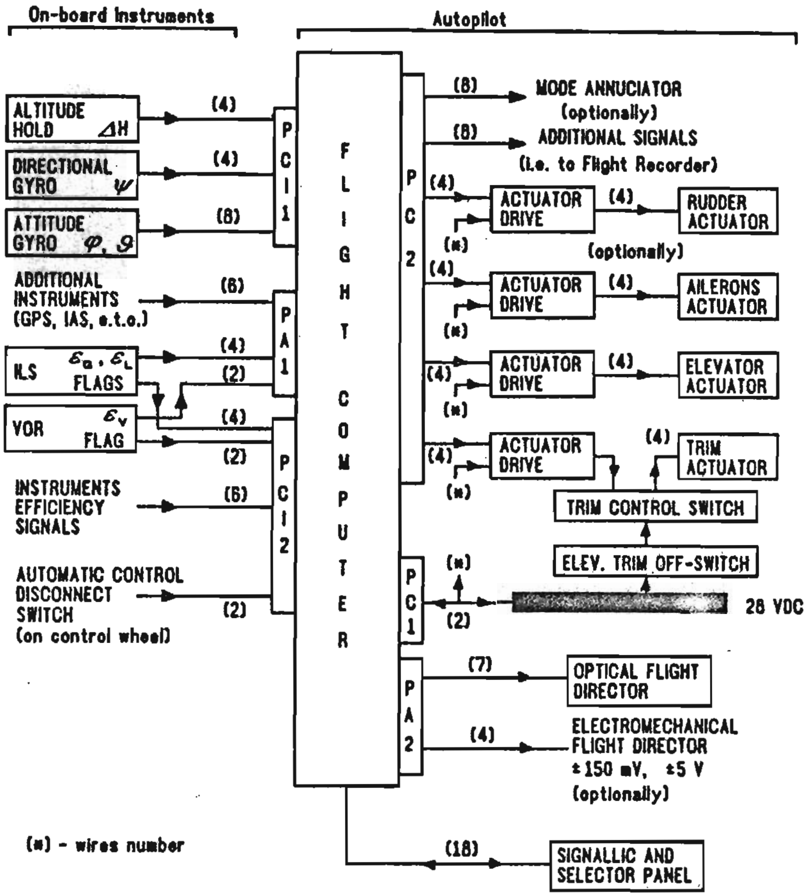

Fig. 2. Block-diagram of the APC-1 Autopilot and the Flight Director hardware

- diagnostic console (optionally).

Additionally some on-board instruments are used

- gyrohorizon
- directional gyro
- altitude compensator
- VOR/ILS receivers
- switch disengaging the autopilot (on control wheel)
- trim control switch (on control wheel)

– additional mode annunciator (optionally).

The device may be optionally equipped with one of two different operator consoles. On the basic console, the autopilot selector panel enables the pilot to engage/disengage the autopilot, select any mode of operation and receive signals denoting how effectively the autopilot functions. The optional console provides additional diagnostic functions assigned for all kinds of on-board service jobs.

2.3. Software structure

The autopilot efficiency and reliability are determined by software which was worked out so that the autopilot functions in a real-time environment (Fig.3).

From a control theory point of view the autopilot is a non-linear, multi-input and multi-output digital PID controller, which executes additional logical operations and generates steering signals of the actuators (cf Bociek et al., 1989a,b; Tomczyk, 1992).

The APC-1 autopilot has a built-in-test (BIT) system (Dołęga and Tomczyk, 1989). When the autopilot is engaged, the controller performs an autotest which determines what types of available autopilot modes will be operational. Because external devices permanently send signals of their efficiency to the controller, a combination of those signals during External Devices Test determines possible modes. The next module tests the selector panel keys and signalling LEDs. The analog test channel checks the correctness of supply voltages, addressing, and performance of the analog signals commutator, respectively. The correctness of A/D conversion is verified by processing four successive reference voltage signals. The main program executed in a short loop contains only auxiliary subroutines. The main logic and arithmetic calculations (for example control signals calculation) are executed in the NMI (non-maskable) and INT (maskable) time interruption modes. Both interrupts contain specially prepared modules in order to provide on-line verification of software and hardware efficiency.

The autopilot generates analog signals for electromechanical flight director indicators; special signals for optical flight director indicators; and digital signals for external mode annunciator and other on-board instruments (flight recorder, for example), respectively (Fig.3).

The autopilot software is designed according to *"fail-safe"* principle, i.e. each single failure of the hardware or on-board instruments can not cause a fail to danger. All failures are signalized on the selector panel and mode annunciator, and the safe autopilot operation mode is chosen automatically.

The present version of APC-1 autopilot is the APC-1P, one which is adjusted to "Piper Seneca II" aircraft and Edo-Aire on-board instruments. It is easy to

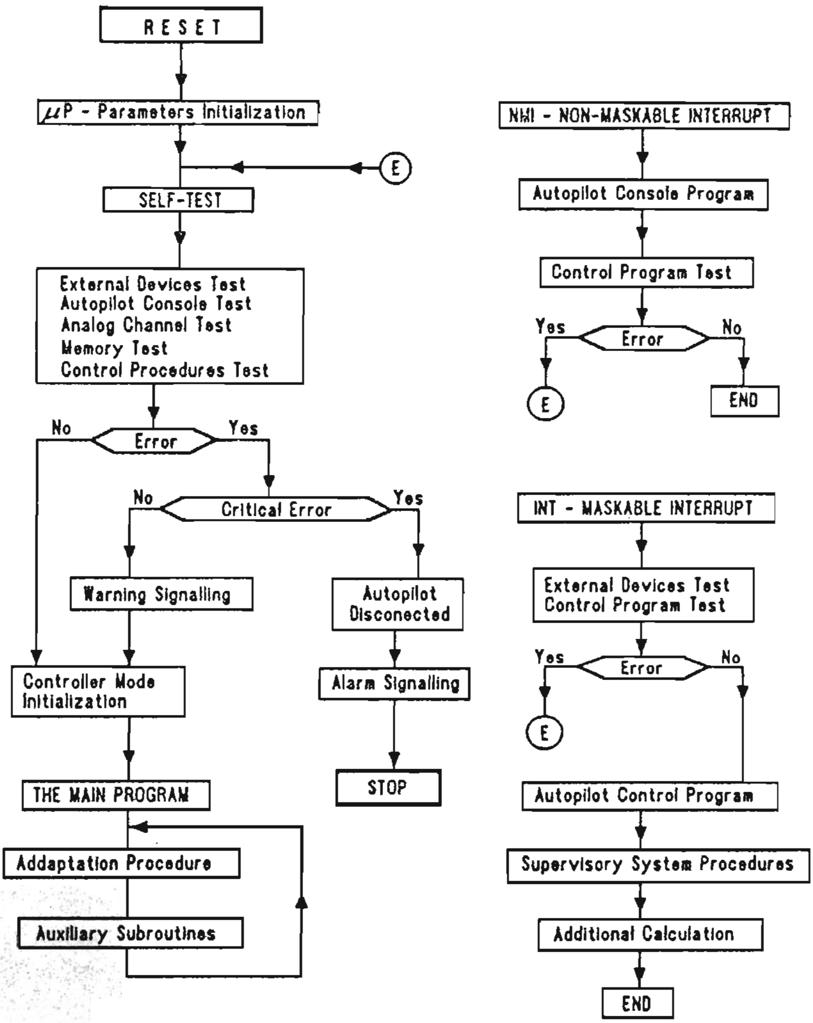

Fig. 3. APC-1 Autopilot software block-diagram

adopt this autopilot to other light aircraft and on-board instruments, since all modifications can be made by software.

3. Tests of the autopilot

The APC-1P autopilot laboratory and flight tests were made according to the Polish National Civil Aviation Administration requirements. The flight test programs and reports were analyzed and approved by the Certification Division of General Inspectorate of Polish Civil Aviation Administration.

As it was mentioned above the autopilot was subjected to laboratory tests. The testing system consisted of microcomputer AT with specialized coupling modules and a specialized mechanical device, simulating real forces applied to electrical servos of the autopilot. The computer worked as a real-time, instruments-like signals generator, data receiving and monitoring device. The results of the laboratory verification of established control laws, concerning both software and hardware were rather optimistic and suggested that the autopilot would be able to perform designated control actions efficiently.

Although the experiments were kept in almost real-like conditions, flight tests are the most powerful verification of the project (Dziedzic and Tomczyk, 1992).

It was assumed that six main goals should be reached during the tests

- estimation of the employed software and hardware solutions
- estimation of the autopilot efficiency and reliability
- the autopilot modules regulation in real-conditions usage
- obtaining conditions of the safe usage of the autopilot
- improving exploitation experience
- obtaining the certificate if the autopilot parameters and features are meeting the certificate requirements.

3.1. Equipment

The tests were carried out on the PZL M20 "Mewa" aircraft and during test flights over 50 parameters were intercepted. These parameters are functionally divided into five groups

- parameters describing the airplane attitude, speed and altitude, respectively

- signals from navigation instruments
- aerodynamic control surfaces deflections
- the autopilot internal signals (analog and digital)
- others: time, markers, supply voltage, etc.

All the data were received and stored by means of PSR-03E data recording system. The system was designed and made at Technical University in Rzeszów in 1982 ÷ 86 (Grzybowski and Tomczyk, 1989). The PSR-03E consists of four modules

- central unit with operator's console
- remote control unit (including digital displays)
- magnetic tape recorder
- power supply unit.

The system makes available to the user 96 unipolar voltage inputs with 8-bit A/D converter, 16 parallel 8-bit digital inputs and 8 inputs of digital reverse counters with capacity of 256 impulses. The basic frequency of sampling is 10, 20, 25, 50 or 100 Hz in every channel with possibility of increasing if by means of the measurement frame modification. Digitalized data are recorded on the magnetic tape as a 8-bit parallel word with the 9th non-parity check bit. The registration time depends on the kind of magnetic tape, it is usually greater then 30 and less then 60 min. The system satisfies all technical requirements according to Polish Standarts.

Intercepted data are subsequently transformed, filtered and analyzed by means of the ground data analysis workstation. The workstation includes two basic subsystems

- the reading device (reads the magnetic tape)
- the AT microcomputer supplied with two displaying monitors which controls the tape reading station, stores intercepted data on disk and performs data adjusting and filtering. The obtained data are presented in graphics or schedule form.

3.2. Methodology and results

The in-flight tests followed short ground research of the autopilot with the device built-on on the board of the airplane.

During 25 hours of test flights over 500 min. of registration time have been recorded[2] and stored on floppy-discs (about 70 Mb of data).

The experiments included several sub-tests presented below. All the tests were carried out under many different conditions depending on the air speed, the altitude, the mass of airplane and the center of gravity position, configuration of landing gear, flaps, power plant rating etc.

There are three main groups of the flight tests

- Safety of the autopilot operation
- Airplane control quality analysis
- The autopilot tests under abnormal flight conditions.

Some tests results are presented in the Fig.4 ÷ Fig.11, with the following denotations

ϑ	–	pitch angle [dg]
φ	–	roll angle [dg]
V	–	airspeed (IAS) [kt]
ε_L	–	LOC deflection [dg]
ε_G	–	GS deflection [dg]
δ_A	–	ailerons deflection [dg]
δ_E	–	elevator deflection [dg]
H	–	height [m]
h	–	altitude deflection [m]
ψ	–	heading deflection [dg]
r	–	turn rate [dg/s]
U_s	–	supply voltage of elevator servo [V]
t	–	time [s]
V_0	–	initial airspeed of test [kt]
H_0	–	initial altitude of test [m]
c.g.	–	center of gravity position [m]

3.2.1. Safety of the autopilot operation

- Test of the autopilot engaging/disengaging switch and electrical decouplers reliability.

Results of this test directly influenced safety of all subsequent tests, no failures were observed, forcing manual control with the autopilot "on" was possible.

[2]cf Tomczyk A., (red), Sprawozdanie z prób w locie autopilota APC-1P na samolocie PZL M20 Mewa, Politechnika Rzeszowska, Dokumenty nr RM/LI-115/90, 23/91, 29/91, 53/91, 32/92, Rzeszów, 1990-92 (unpublished)

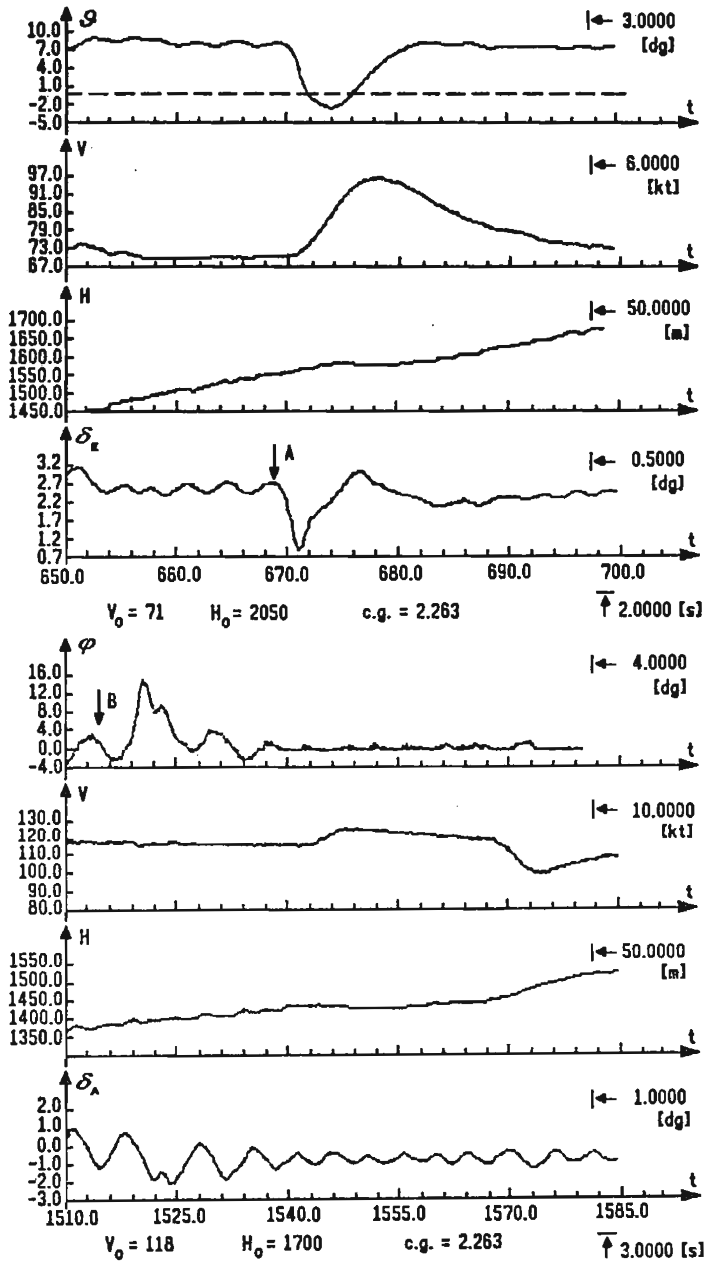

Fig. 4. Pitch angle and bank angle stabilization: **A** – force elevator disturbance, **B** – step deflection of the rudder

- Estimation of the reliability of board instruments and the flight director display.

The gyrohorizon, VOR/ILS receiver, directional gyro, respectively were checked. No disorders were recognized.

3.2.2. Airplane control quality analysis

- Estimation of efficiency of the attitude control and stabilization.

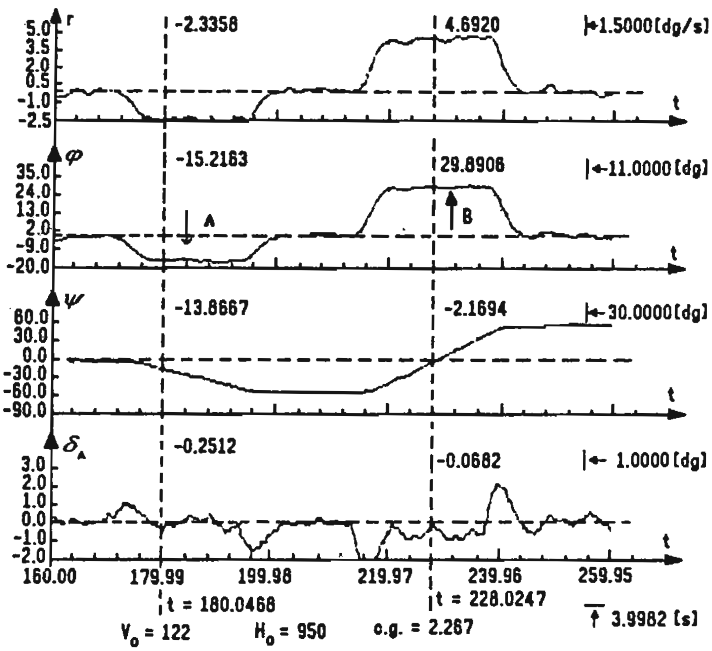

Fig. 5. Roll control: **A** – a standard turn, 15 dg bank angle; **B** – 30 dg bank angle turn

The correctness of regulation quality, the steady-state regulation error and transitory states after a steady-state disturbance were analyzed. Some examples from obtained materials are depicted below. Figure 4 presents pitch and roll stabilization after disturbance caused by an adequately elevator and rudder forced deflection. Figure 5 presents roll control during horizontal steady-flight standard turns through 15 and 30 dg were forced. The error of pitch angle stabilization was less than 0.4 degree in good meteorological conditions and the bank angle error was not bigger than 1.1 degree. Time history diagrams of the pitch and roll control process are correct.

The final attitude stabilization errors are caused by

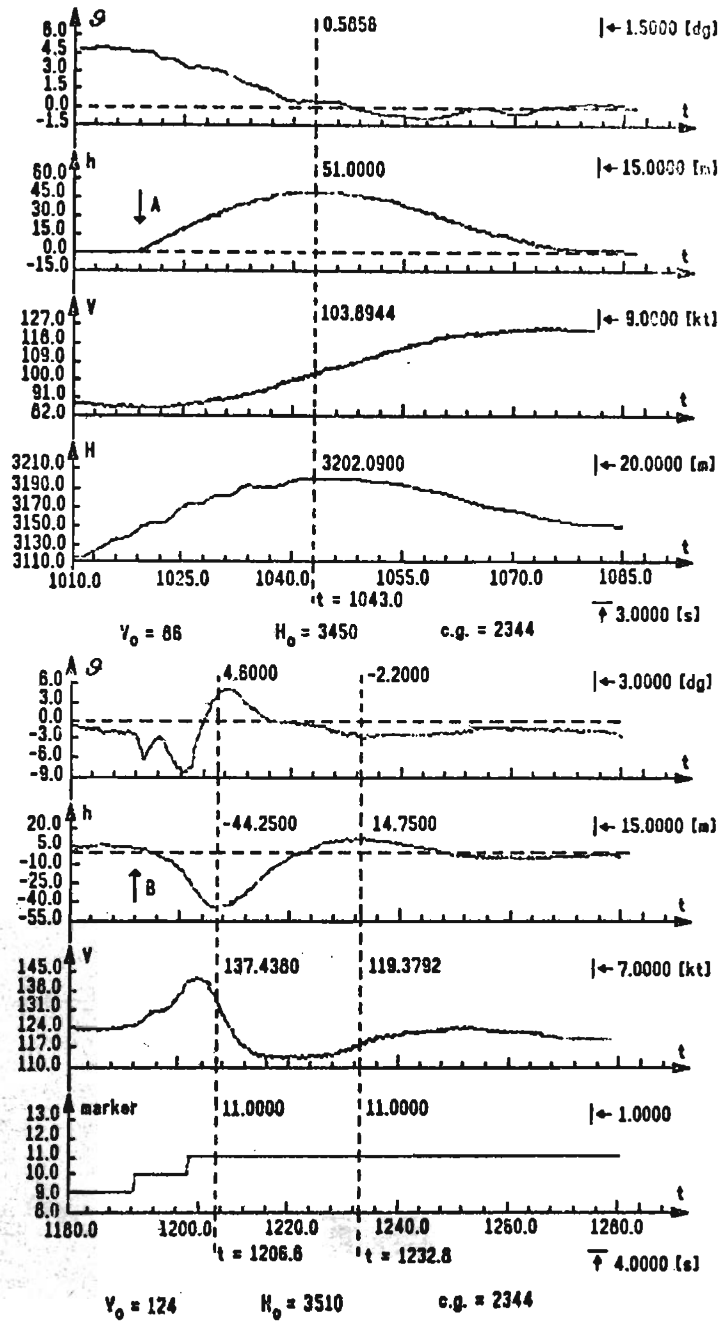

Fig. 6. Altitude coupling process and altitude stabilization: A – the ALT button was pressed, initial vertical speed $V_z = 3.7$ m/s; B – handling force elevator disturbance

- on-board instruments errors
- discretization and quantization of all input signals
- fix-point microprocessor arithmetic
- discretization and quantization of actuators output signals (deflection of aircraft control surfaces)
- non-linearity effects (for example: the clearance of the primary aircraft control system, actuators nonlinearities, etc.).

• Flight along given trajectory i.e. heading and altitude stabilization tests.

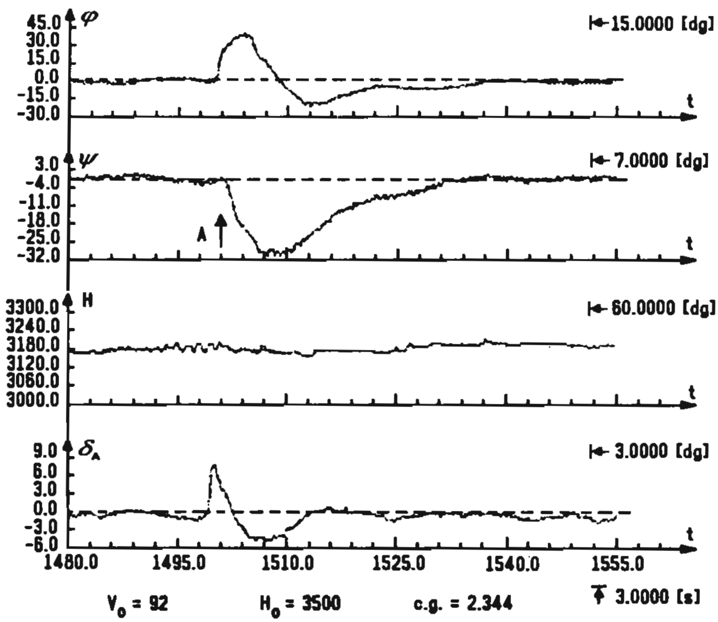

Fig. 7. Heading coupling and course stabilization: **A** – the new heading was selected

The altitude stabilization during climbing flight (vertical speed was 3.7 m/s) was engaged. The deflection recorded during horizontal steady-state flight was less then 15 m (Fig.6). The course coupling process was correct and the deflection of the selected heading did not exceed 2.5 dg (Fig.7).

• VOR and ILS navigation.

No unexpected problems appeared. VOR radial intercepting and tracking was correct in spite of the high-level disturbances received by VOR receiver. Figure 8 presents ILS approaching more earth. At an altitude of 50 m, 1000 m far from the runway threshold, the trajectory deflections were less then 0.25 dg for the localizer and 0.1 dg for the glide slope beam tracking.

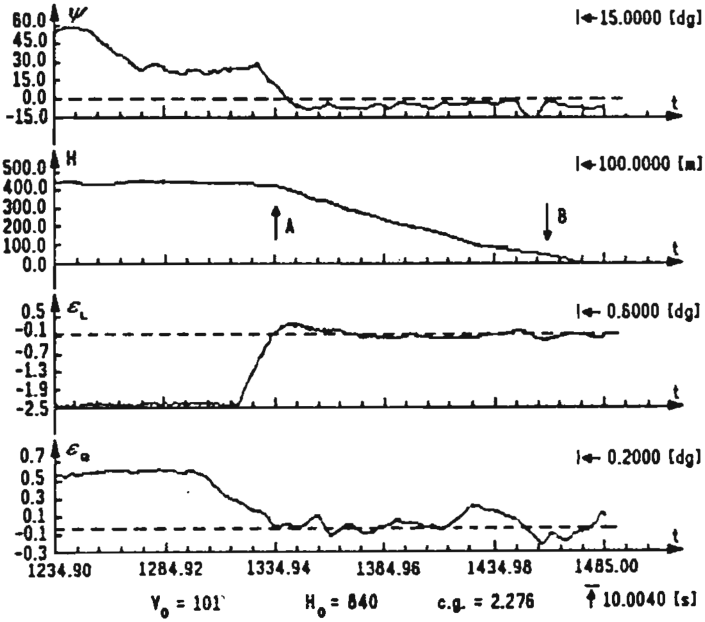

Fig. 8. ILS approach to land: **A** – the glide slope coupling, **B** – the Decision Height (DH) for ICAO Cat.I approach (60 m)

The position of airplane was good for landing, in accordance with the ICAO Cat. I requirements.

3.2.3. The autopilot tests under abnormal flight conditions

Several critical failures of the aircraft and the autopilot were simulated during the flight; the typical tests are described bellow.

• Propeller thrust asymmetry.

During the climbing flight with minimum control speed (V_{MC}) and start power of engines, one engine was cut-off. The autopilot efficiency was enough for the aircraft attitude stabilization (see Fig.9).

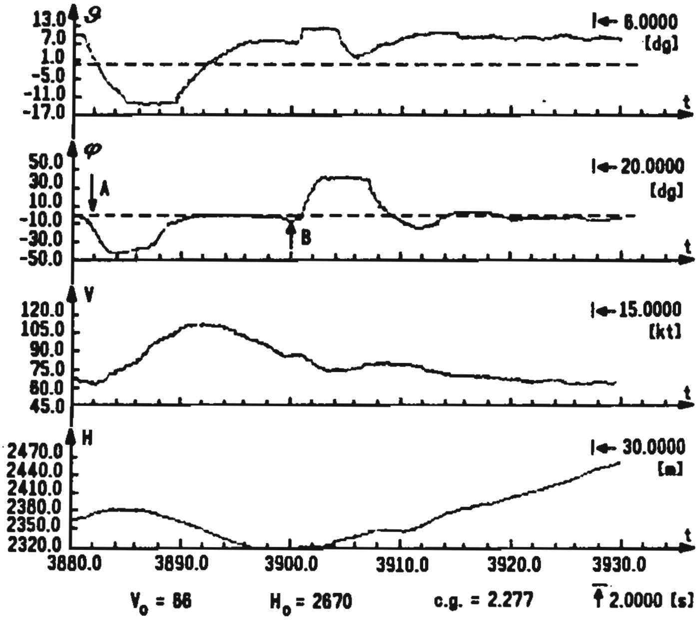

Fig. 9. Effect of the left engine cut-off: **A** – the engine is cut-off, VIAS = 66 kt (V_{MC} = 70 kt); **B** – the left engine starts again

- The flaps malfunction.

The maximum flaps deflections (and return) were forced at the maximum flaps speed of aircraft (V_{FE}). The control process was correct and primary pitch angle was stabilized (Fig.10).

- The autopilot power supply failures.

The autopilot clutches were disconnected and a manuel piloting of the aircraft was possible.

- VOR/ILS signals disappearance.

During VOR navigation flight and ILS approach the receiver frequency was changed. VOR/ILS signals disappearance was signalized and the safe modes of operation were chosen automatically, i.e. time-variable value of roll or/and pitch angle were stabilized.

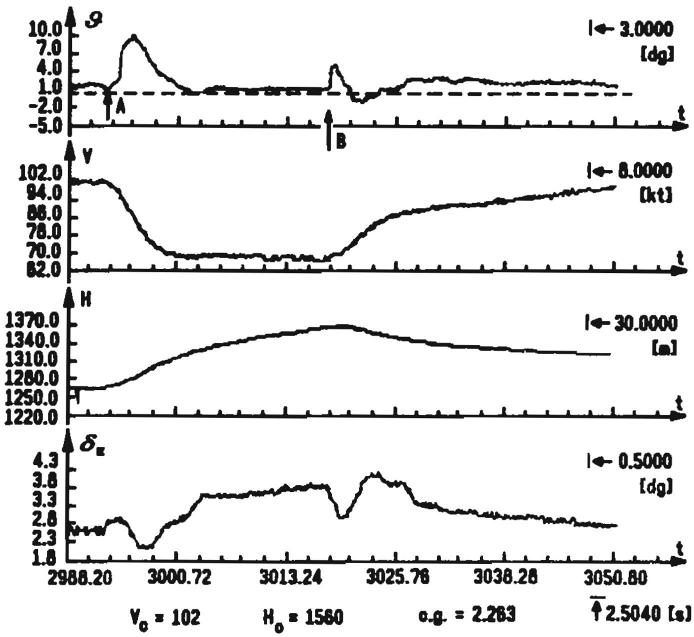

Fig. 10. Pitch angle control process after flaps deflections: **A** – the step deflection of flaps (40 dg), VIAS = 102 kt ($V_{FE} = 107$); **B** – the flaps were returned to initial position (0 dg)

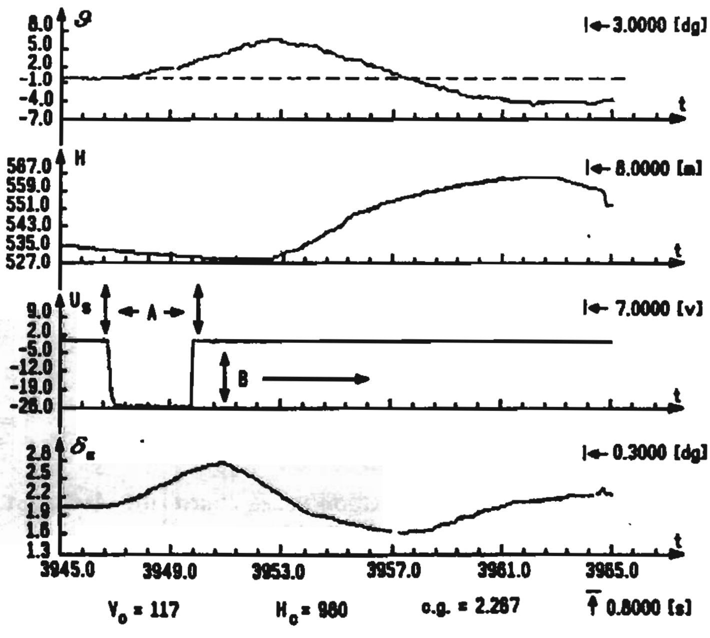

Fig. 11. Ailerons servo failure effect and the pilot's response to an autopilot malfunction; **A** – the elevator servo non-controlled work (max rotational speed); **B** – the beginning of the pilot's reaction

- Putting servos out of control.

The critical failure of the autopilot is a non-controlled work of servo which effects in the maximum speed of control surfaces deflections. The requirements of the Aeronautical Standards establish that pilot reaction delay time is three seconds maximum.

Figure 11 depicts elevator servo failure and pilot's reaction correcting the pitch angle. The airplane attitude changes were slow and allowing the pilot to overtake suitable action without exceeding conditions of safe exploitation.

The failure detection and its indications in all these situations were correct.

4. Conclusions

The tests confirmed reliability and efficiency of the autopilot. The results met FAR23 requirements, TSO-C9c and AS402A Standards.

Because of the flight safety, the autopilot tests demand the special attention. The final opinions of the automatic flight control system quality are made by pilots. Test pilots opinions about APC-1P autopilot were good and they have recommended to use it in normal exploitation. All tests were made under the General Inspectorate of Polish Civil Aviation Administration superintendence.

Production of the autopilot is prepared by the Advanced Technology Manufacturing Inc., Warsaw, and the APC-1P autopilot will be used on PZL M20 "Mewa" ("Piper Seneca II") board.

The experiments created the source of very precious scientific and didactic materials. The experience being obtained will be helpful in designing and testing the next aircraft control systems.

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Wybrane wyniki prób w locie cyfrowego autopilota APC-1P

Streszczenie

W pracy przedstawiono strukturę cyfrowego układu sterowania samolotem, przedstawiono podstawowe własności funkcjonalne autopilota APC-1P oraz krótki opis jego rozwiązań sprzętowych i programowych. Przedstawiono cel i metodykę badań w locie pokładowych układów sterowania oraz podstawowe własności aparatury pomiarowej. Rezultaty prób w locie ilustrowane są wykresami uzyskanymi w próbach w locie na samolocie PZL M20 "Mewa".

Na podstawie wyników badań laboratoryjnych i w locie dokonano oceny własności cyfrowego układu automatycznego sterowania samolotem oraz sformułowano wnioski stwierdzające, że badany autopilot APC-1P może być stosowany w samolotach lekkich i lokalnej komunikacji budowanych wg przepisów FAR 23, uznanych za standard dla tej klasy samolotów.

Doświadczenia zespołu badawczego projektującego i testującego autopilota kontynuowane są w kolejnych pracach badawczych i projektowych nad lotniczymi systemami sterowania.

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