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FLIGHT MANAGEMENT SYSTEMS - AUTOMATIC FLIGHT CONTROL

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Flight management systems (FMS) present the top of automation of all aircraft behavior and control beginning from improvement of aircraft dynamics by means of subsystems of artificial stabilization through autopilot and aircraft guidance to various sorts of optimizations of the whole flight, including flight plan creation and adaptation according to flight conditions provided by means of automatic and semi-automatic systems of various levels, komplexity and technical means. It is obvious that such a complicated system can be analyzed from several points of view as we see in following.

Key words: flight stabilization, autopilot, flight guidance, flight control systems, flight management systems, automatic and semi-automatic systems, glide slope path, aircraft dynamics and kinematics, coordinated lateral-directional motion.

1. Aircraft control

It is possible the pilot's activity during aircraft stabilization and flight control roughly divide into four areas: information acquisition about aircraft motion around its center of gravity and aircraft position to its track, then follow its judge, create a decision about aircraft control and finally control of aircraft basically by means of control wheel, rudder pedals and throttle.

This pilot's activity can be automated partially or fully. Then we talk about semi-automatic control and automatic control, which can be provide on various stages of technical and hierarchical levels.

Semi-automatic control involves human operator into close-loop circuit: aircraft (AC) - pilot (P) as we see on basic scheme in Fig. 1-1. It is obvious; there are two types of these semi-automatic control systems. These systems create from one side power - dynamic

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connection between pilot's muscular activity - its effector (E) and above mentioned aircraft control means commonly here designated as control levers (CL). From the other side they create information connection between aircraft outputs containing mostly flight data and navigation data (FD, ND) here commonly signed as measured data (MD) and pilot's input - its receptors (R).

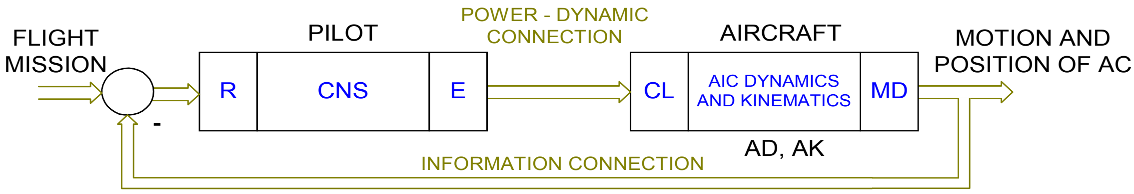

Fig. 1-1 - Connections in closed loop: pilot - aircraft

R *Receptors,* ***CNS*** *Central Nervous System,* ***E*** *Effectors – Muscular Activity,* ***CL*** *Control Levers,* ***AD*** *Aircraft Dynamics,* ***AK*** *Aircraft Kinematics,* ***MD*** *Measured Data,* ***FD*** *Flight Data,* ***ND*** *Navigation Data,* ***ED*** *Engine Data.*

The first connection is created by means of systems of artificial stabilization which contain stability augmentation system and control augmentation systems in order to adapting the nonadvantageous (if exists) aircraft qualities to the limited abilities of human operator. The another subsystem of this connection can be system of artificial feeling in the case that aircraft is equipped with power-assisted system (high-performance aircraft) containing other subsystems.

The second connection i.e. information connection unable to the pilot to create information model of aircraft behavior in which flight and navigation variables, alerts, environment are integrated and presented in convenient configuration to make easily and precisely decision. The systems creating this coupling are primary displays, currently now created by Primary Flight Display provided by Flight Director system as well and Navigation Display.

The systems of automatic control of aircraft can be divided into local significance systems and global significance systems. Local significance systems of aircraft automatic control we furthermore divide into systems of aircraft stabilization around its center of gravity which is accomplished by means systems called automatic pilot, shortly autopilot and the systems of automatic aircraft guidance called flight control systems which contain autopilots in their inner loop.

Global significance systems of aircraft control are flight management systems which include all systems of aircraft control automatic and semi-automatic systems of all levels as we will see later.

2. Flight management systems

Flight management systems (FMS) conceive the highest stage of aircraft automatic and semi-automatic control. Possible structure scheme of flight management system is shown on Fig. 2-1. From this figure follows that the central part of flight management system containing flight management computer (FMC) and control and diplay unit (CDU) is surrounded by sources of information created by blocks on the left side with navigational data and flight ones. Next block contains performance characteristics of aircraft its air-frame with its engines and manuals with flight and bort procedures as well. Blocks on the top of this scheme are sources of environmental information including role of the pilot. The outputs of flight management system are located on the right side of this scheme with their blocks of optimization, aircraft control and displaying units.

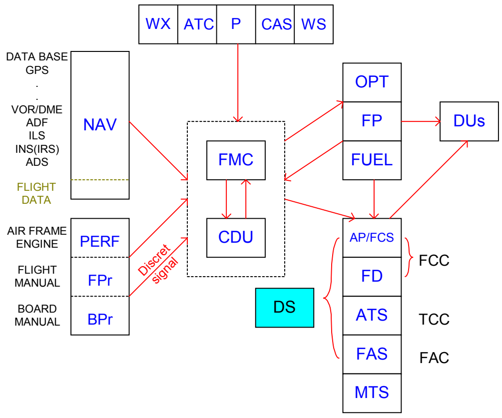

Fig. 2-1 - Structural scheme of FMS

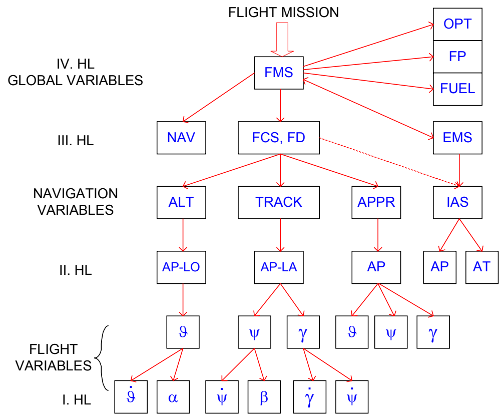

Fig. 2-2 - Hierarchical levels of FMS

FMC *Flight Management Computer,* ***CDU*** *Control Display Unit,* ***NAV*** *Navigation information,* ***IRS/INS*** *Inertial Reference/Navigation System,* ***ADS*** *Air Data System,* ***PERF*** *Performances of airframe and engines,* ***WX*** *Weather Radar,* ***ATC*** *Air Traffic Control,* ***P*** *Pilot,* ***CAS*** *Collision Avoidance System,* ***WS*** *Wind Share,* ***FP*** *Flight Plan,* ***FUEL*** *Plan of fuel consumption,* ***OPT*** *Optimization,* ***FCC*** *Flight Control Computer,* ***AP/FCS*** *Automatic Pilot / Flight Control Systems,* ***FD*** *Flight Director,* ***TCC*** *Trust Control Computer,* ***ATS*** *Auto-Throttle System,* ***FAC*** *Flight Augmentation Computer,* ***FAS*** *Flight Augmentation System ,* ***BPr*** *Board Procedures,* ***FPr*** *Flight Procedures,* ***DU*** *Display Units,* ***PFD*** *Primary Flight Display,* ***ND*** *Navigation Display,* ***EICAS*** *Engine Indication and Crew Alert System,* ***ECAM*** *Electronic Centralized Aircraft Monitoring,* ***MTS*** *Monitoring and Test System*

NAV *Navigation,* ***FCS/FD*** *Flight control system/flight director,* ***EMS*** *Engine management system,* ***ALT*** *Aircraft guidance in vertical plane,* ***TRACK*** *Aircraft guidance in horizontal plane,* ***APPR*** *Approach, Aircraft guidance on ILS path,* ***IAS*** *Indicated Air Speed stabilization,* ***AP-LO*** *Automatic Pilot of Longitudinal Motion,* ϑ *Stabilization of Pitch Angle,* ***AP-LA*** *Automatic Pilot of Lateral Motion,* ψ *Stabilization of Yaw Angle,* γ *Stabilization of Roll Angle,* ***AT*** *Auto-throttle,* $\dot{\vartheta}$ *Pitch Rate Stabilization,* $\dot{\psi}$ *Yaw Rate Stabilization,* $\dot{\gamma}$ *Roll Rate Stabilization,* α *Angle of Attack Stabilization,* β *Side-slip Angle Stabilization*

It is obvious; flight management system is large-scale system with its typical features and properties. Such a complicated system we can't analyze in its complexity and we usually decompose it into a set of subsystems from several points of view according to our interest. For the purposes of automatic control we can distinguish several hierarchical levels of automatic control loops. In this separation of the whole system we proceed usually from the highest hierarchic level to the lowest hierarchic level. In solution of these levels (design of systems of automatic control) we proceed usually in opposite way, from the lowest hierarchic level to the highest hierarchical levels and seek the connection between these levels.

One of possible decomposition according to above mentioned hierarchical control loops is shown by schematic diagram in Fig. 2-2 in which are four hierarchical levels presented.

The highest hierarchical level processes global variables, creates flight plan (FP), plan of fuel consumption (FUEL), ensures optimization (OPT) of all control processes according various criteria and flight phases and makes decisions-logical control- about the ways of flight guidance from take-off of aircraft through its climbing, cruise flight, descending to the approach area to the final approach and landing (according its certification to the weather minims).

The third hierarchical level provides aircraft guidance in both horizontal and vertical planes according to optimization and decision of master-i.e. fourth hierarchical level. This level uses navigation variables: radio-navigation variables and aerometrical ones and governs the slaved second hierarchical level. Special case is automatic control of indicated air speed (IAS) which can be accomplished either in the third hierarchical level or can be coordinated with the four hierarchical level by means of engine management system (EMS). The control systems which accomplish automatic control of navigation variables of this hierarchical level are flight control system / flight director system and auto-throttle / auto-trust system with their computers.

The second hierarchical level provides automatic stabilization of aircraft motion around its center of gravity; it means stabilization of three aircraft position angles. This control level commonly with the first hierarchical level provides stabilization of aircraft dynamics. Both these hierarchical levels use flight variables and are accomplished by means of autopilots with their servomechanisms.

The first hierarchical level is usually connected with the master second control level in position of inner slaved loop. It makes aircraft dynamics better in correspondence to original ones and separately is a part of semi-automatic control in systems of artificial stabilization.

The systems of all these three hierarchical levels are dynamic ones. It means we can describe them by means of differential equations or any other art of input-output description and by inner description - state space description and for they syntheses use methods known in theory of automatic control but with regard on aircraft quality specification. Connection between flight stabilization and flight guidance, i.e. connection between the second and the third hierarchical level is created by means of kinematics equation

$$\dot{H} = V_0(\vartheta - \alpha) + U_Y \qquad ; \qquad \dot{Z} = V_0(\psi - \beta) + U_Z \tag{1.1}$$

in which: H and Z are linear deviation from track in vertical and horizontal plane
V_0 is constant speed of aircraft
U_Y and U_Z are vertical and horizontal component of wind.

In the next part we present like specimen of automatic control systems two examples of these systems in the third hierarchical level and in the second one. In first example we will formulate a problem of aircraft guidance in glide-slope plane as an example of automatic control in the third hierarchical level which is the most important phase of final approach. The second example will be devote to the stabilization and control of coordinated lateral-directional aircraft motion which is the basic mode (HDG) of lateral autopilot and contain the first and the second hierarchical level together.

3. Final approach in Glide Slope

Final approach is the most important flight phase. On its successfulness depends in great deal the success of the whole flight. For solution such a task we need in addition to the knowledge of aircraft dynamics to know aircraft kinematics as well which are rather complicated to those of aircraft guidance in cross flight (see Eq. 1.1). The derivation of this kinematics is the matter of the following part. In following we will assume the flight in glide slope (GS) plane with aircraft centered horizontally to the approach path but flying above this glide slope. This situation with all needed values and variables is presented on Fig. 3-1, where the aircraft glide-slope deviation ε_{GS} is the basic controlled variable.

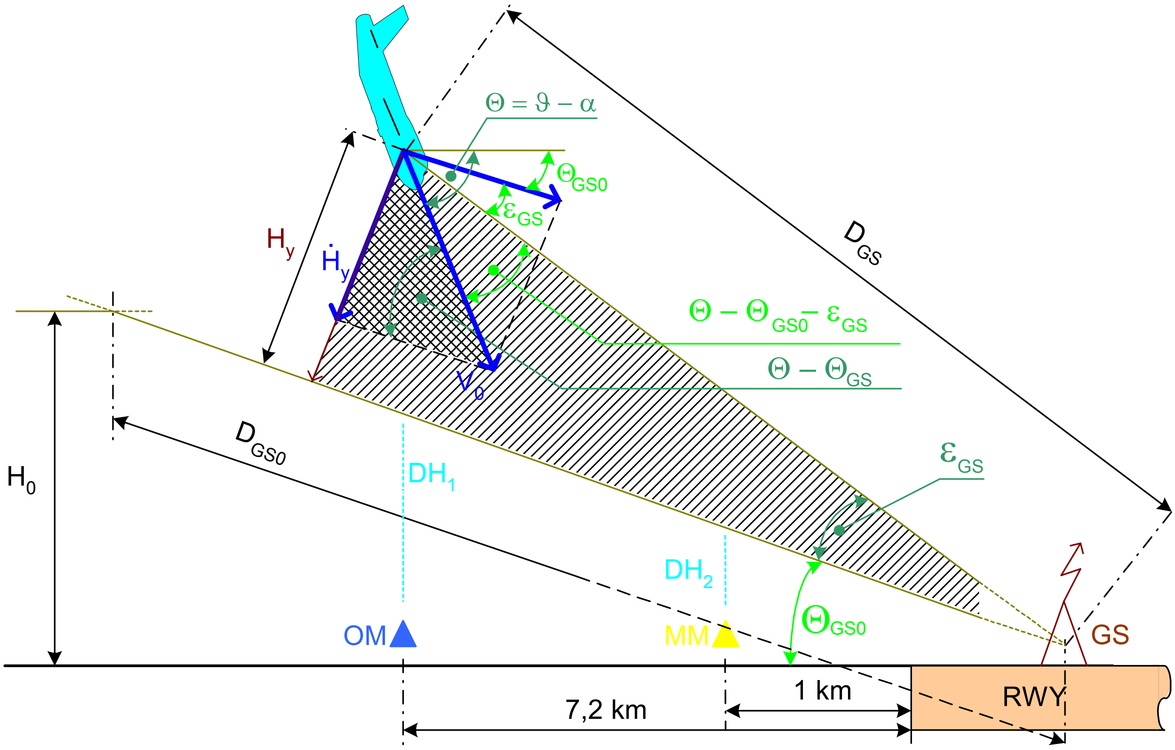

Fig. 3-1 – Aircraft guidance in glide slope plane - kinematics

From this figure and two triangulars in it, follow relations

$$\frac{H_y}{D_{GS}} = \sin\varepsilon_{GS}\,; \qquad \frac{\dot{H}_y}{V_0} = \sin(\Theta - \Theta_{GS0}) \tag{1.2}$$

After their linearization and substitution we obtain integral equation

$$\varepsilon_{GS} = \frac{H_y}{D_{GS}} = \frac{V_0}{D_{GS}} \cdot \int_0^T (\Theta - \Theta_{GS0})dt \tag{1.3}$$

in which we express the term D_{GS} by means of the next relation

$$D_{GS} = D_{GS0} - V_0 \cdot \int_0^T \cos(\Theta - \Theta_{GS0} - \varepsilon_{GS})dt \doteq D_{GSO} - V_0 t \tag{1.4}$$

Consequently we receive final integral equation in the form

$$\varepsilon_{GS} = \frac{1}{T_0 - t} \cdot \int_0^T (\Theta - \Theta_{GS0})dt\,; \quad \text{where } T_0 = \frac{D_{GS0}}{V_0} \tag{1.5}$$

which can be prescribed into differential equation

$$(T_0 - t)\dot{\varepsilon}_{GS} - \varepsilon_{GS} = \Theta - \Theta_{GS0} \tag{1.6}$$

This linearized equation is the equation of unstable system with time-variable coefficient. This situation put serious demands on control system on the aircraft guidance on glide-slope plain. Control system must by certain way during the final approach reduce increasing gain in the loops of ε_{GS} and $\dot{\varepsilon}_{GS}$. Common block scheme for this specific aircraft guidance we can express as follows on Fig. 3-2.

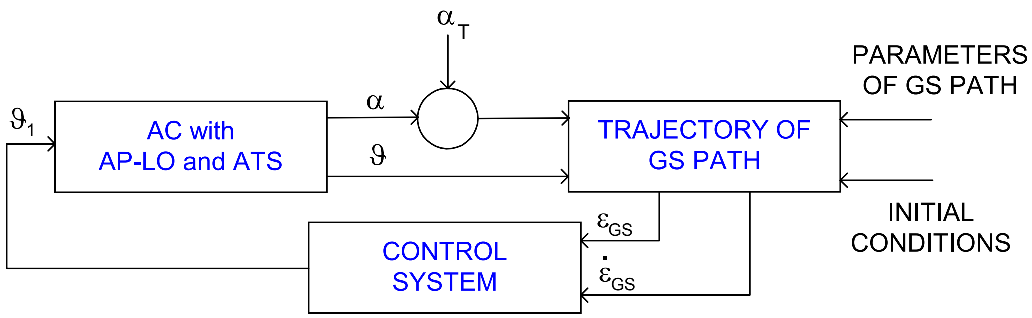

Fig. 3-2 - Common structure scheme of aircraft guidance in GS path

Common equation of the control system from Fig. 3-2 we can express like in Eq. (1.7)

$$\vartheta_1 = N_1(K_\varepsilon \cdot \varepsilon_{GS}) + N_2(K_{\dot\varepsilon} \cdot \dot\varepsilon_{GS}) \tag{1.7}$$

where N_1 and N_2 are nonlinearities, which take in account the Eq. (1.5).

4. Stabilization of lateral-directional motion

Lateral-directional motion of aircraft cab be under certain limitation described by the set of deviate differential equation linearized in the point of flight envelope of our interest

$$\dot\beta + b_{11}\beta + b_{12}\gamma - \dot\psi = d_{12}\delta_s \tag{1.8}$$

$$b_{21}\beta + \ddot\gamma + b_{22}\dot\gamma + b_{23}\dot\psi = d_{21}\delta_k + d_{22}\delta_s \tag{1.9}$$

$$b_{31}\beta + b_{32}\dot\gamma + \ddot\psi + b_{33}\dot\psi = d_{31}\delta_k + d_{32}\delta_s \tag{1.10}$$

Or in matrix relation

$$[A_1]\vec{y} = [B_1]\vec{u} \tag{1.11}$$

Where: $\vec{y} = [\beta, \gamma, \psi]^T$ is output vector: side-slip angle, roll angle and yaw angle respectively.

$\vec{u} = [\delta_k, \delta_s]^T$ is input vector: aileron deviation and rudder deviation.

This system is unstable due to spiral unstability in characteristic polynomial (root s_5 positive)

$$N(s) = s^5 + B_4 s^4 + B_3 s^3 + B_2 s^2 + B_1 s = s(s^2 + 2a\omega_n s + \omega_n^2)(s + s_4)(s - s_5) \tag{1.12}$$

Bloc scheme of automatic stabilization is shown on Fig. 4-1 and corresponding transients for coordinated heading change are shown in Fig. 4-2.

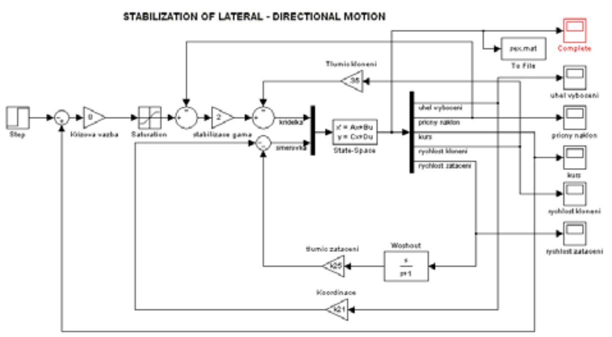

Fig. 4-1 - Schematic model of lateral autopilot

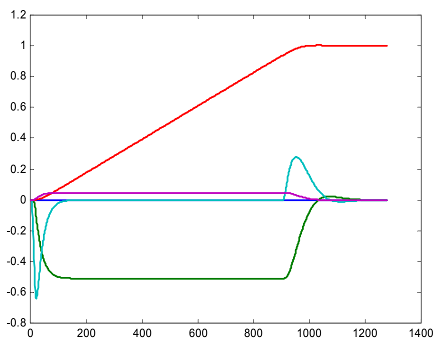

Fig. 4-2 - Outputs of Control system

Problems connected with aircraft automatic control systems and identification of aircraft dynamics are the subjects of education and research of our department.