Automatic Command Systems for the Flight Direction Control during the Landing Process

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***Abstract*— The aircraft pilot must cancel the aircraft lateral deviation with respect to the runway before the starting of the landing process. This is made by means of automatic command systems for the flight direction control with radio navigation system and equipment for the measurement of the distance between the aircraft and the radio marker. In this paper the authors present two such systems: an automatic command system for the flight direction control and an automatic command system for the flight direction control with radio navigation system and DME (the equipment for the measurement of the distance between the aircraft and the radio marker). For the orientation and stabilization of the aircrafts on the runway direction, the second system may be used with good results. This system is tested by means of numerical simulations in Matlab environment for a light aircraft.**

I. Introduction

The landing process is simplified if the aircrafts movement in lateral plane is made without errors (deviation of the aircrafts from the runway direction is zero). That is why the systems for the automatic command (control) of the flight direction are very important.

The aircrafts are controlled during the cruise flight so that they follow the signals provided by the direction radio marker; the control is made, in the most of the cases, by means of VHF Omni directional Range (VOR) navigation system. This system is used with equipment (DME) for the measurement of the distance between the aircraft and the radio marker. During the landing process, the VOR system is replaced by the Instrumental Landing System (ILS) and the radio marker direction is, in this case, the runway direction (Fig. 1) [1].

For the aircrafts landing process the Automatic Landing Systems (ALSs) are used. The first Automatic Landing System was designed in England in 1965. From that moment, most aircrafts have ALS based on the Instrumental Landing System (ILS) for the aircrafts control [1], [2] by using proportional-derivative (PD), proportional-integral (PI) or proportional-integral-derivative (PID) conventional laws for the altitude and descend velocity control [3], [4], [5], and PD or PID conventional laws for the pitch angle and pitch rate control.

The use of GPS and the increase of the sensor performances lead to the increase of the landing trajectory track accuracy [6], [7], [8], [9]. The sensor errors must have an insignificant influence on the landing process performances.

For different flight conditions, the controlled parameters should be kept in a specific flight envelope, defined by the Federal Aviation Administration (FAA). The environment conditions required by FAA are: head wind – 25 knots, rear wind – 10 knots, lateral wind – 15 knots, moderate turbulence, wind shears of 8 knots per 100 ft at 200 ft to touchdown [10], [11], [12]. If the flight conditions are outside the specific envelope, then the ALS is disabled, and the pilot takes the aircraft control. According to the international statistics, 62% of aircraft accidents are due to the atmospheric disturbances (wind disturbances).

In recent years lots of scientific researches have applied the intelligent concepts for the aircrafts automatic control during the landing process, by using the optimal synthesis $H_2, H_\infty, H_2 / H_\infty$ [10], [12] and the adaptive synthesis based on the dynamic inversion theory, the neural networks theory [3], [13], and the fuzzy techniques [14], [15], respectively. The intelligent techniques have the advantage of very good adaptability, robustness, and software implementation capabilities

Before the two stages of the landing procedure (the glide slope descend and flare stage) begin, the pilot must cancel the aircraft lateral deviation with respect to the runway. This is made by means of automatic command systems for the flight direction control with radio navigation system and equipment for the measurement of the distance between the aircraft and the radio marker. In this paper the authors present two such systems and test them for a light aircraft.

II. Automatic Command Systems for the Flight Direction Control

The landing approach is considered to be precise if the deviation of the aircraft direction does not overcome 20-30 angular minutes and the deviation with respect to the glide slope is less than 10-15 angular minutes. Thus, in the landing approach stage, deviation of the aircraft mass center must not overcome $\pm 5\,\mathrm{m}$ in vertical plane and $\pm 15\,\mathrm{m}$ in horizontal plane, while, when touching the runway, the maximum errors must be $\pm 0.5\,\mathrm{m}$ in vertical plane and $\pm 5\,\mathrm{m}$ in horizontal plane [2].

The lateral deviation of the aircraft with respect to the radio marker direction is expressed by the course angle $G = \psi - \overline{\psi}$; ψ is the flight aircraft direction measured with respect to the geographic North (the angle between the direction of the velocity vector in horizontal plane $\vec{V}_0$ and the direction of the geographic North), while $\overline{\psi}$ is the radio marker direction. In Fig. 1, λ is the angle, measured in horizontal plane, between the aircraft longitudinal axis and the radio marker direction.

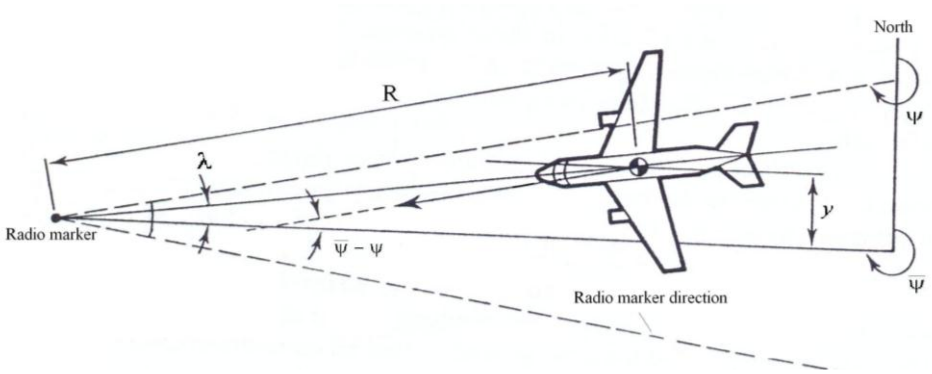

Figure 1. The geometry of the aircraft movement in horizontal plane

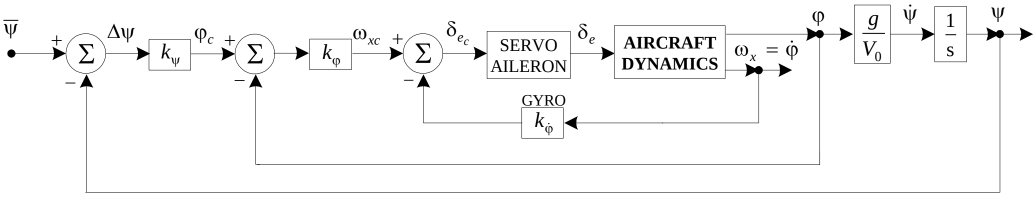

Figure 2. Bock diagram of the automatic command system for the flight direction control

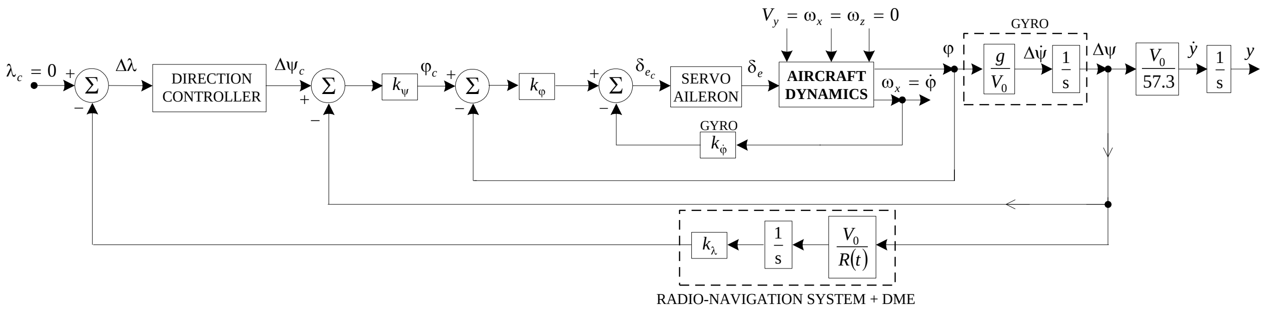

Figure 3. Bock diagram of the automatic command system for the flight direction control with radio navigation system and DME

In Fig. 1, we remark that [1]:

$$\sin\lambda = \frac{y}{R}, \lambda \cong 57.3\frac{y}{R}[\text{deg}], \tag{1}$$

where y is the aircraft lateral deviation with respect to the radio marker direction and R is the distance between the aircraft and the radio marker;

$$R(t) = R_0 - V_0 t, R_0 = R(0). \tag{2}$$

From the velocities triangle it follows [1]:

$$\dot{y} = V_0 \sin\Delta\lambda = \frac{V_0}{57.3}(\psi - \overline{\psi}), [\Delta\psi] = \text{deg}. \tag{3}$$

The equations of the lateral movement of the aircrafts are [5]:

$$\begin{aligned}
&\Delta\dot{\beta} = Y_v \Delta\beta - \Delta\omega_z + \frac{g}{V_{x0}} \cos\theta_0 \Delta\varphi + Y^*_{\delta_d} \Delta\delta_d, \\
&\Delta\dot{\omega}_x = L'_v \Delta V_y + L'_p \Delta\omega_x + L'_r \Delta\omega_z + L'_{\delta_e} \Delta\delta_e + L'_{\delta_d} \Delta\delta_d, \\
&\Delta\dot{\omega}_z = N'_v \Delta V_y + N'_p \Delta\omega_x + N'_r \Delta\omega_z + N'_{\delta_e} \Delta\delta_e + N'_{\delta_d} \Delta\delta_d, \\
&\Delta\dot{\varphi} = \Delta\omega_x + \tan\theta_0 \cdot \Delta\omega_z, \\
&\Delta\dot{\psi} = \frac{\Delta\omega_z}{\cos\theta_0} \cdot
\end{aligned} \tag{4}$$

where β is the aircraft sideslip angle, V_{x_0} – the initial value of the aircraft velocity along the longitudinal axis (Ox), ω_x – the roll angular rate, ω_z – the yaw angular rate, θ_0 – the initial value of the pitch angle (θ), V_y – the aircraft velocity along the lateral axis of the aircraft (Oy), g – the gravitational acceleration, δ_e – the deflection of the ailerons, δ_d – the rudder deflection. The above equation, for a stabilized regime $(\theta_0 = 0)$, if the movement is coordinated $(\dot{\beta} = 0)$, becomes:

$$\dot{\psi} = \frac{g}{V_{x_0}}\varphi \cong \frac{g}{V_0}\varphi. \quad (5)$$

From the above equation it follows that the calculated value of the roll angle (φ_c) is proportional with the yaw angular rate $(\varphi_c \approx \dot{\psi})$; ψ must aperiodically tend to $\overline{\psi}$ and that is why we choose [1]:

$$\varphi_c = k_\psi(\overline{\psi} - \psi) \approx \dot{y} \quad (6)$$

and, taking into account this, equation (5) gets the form:

$$\dot{\psi} + \frac{g}{V_0}\psi = \frac{g}{V_0}\overline{\psi}. \quad (7)$$

If we choose a proportional – derivative (P.D.) control law for the roll angle control, i.e.

$$\delta_{e_c} = k_\varphi(\varphi_c - \varphi) - k_{\dot{\varphi}}\dot{\varphi}, \quad (8)$$

equations (5), (6), (8), together with the dynamic model of the aircraft lateral movement, and the model of the servo mechanism for the aileron actuating, lead to the block diagram from Fig. 2 [1].

By using the information from the navigation system (λ and R), φ_c may be calculated and the control system in Fig. 2 is equivalent with the one in Fig. 3.

The model of the subsystem represented by the navigation system (together with DME – the equipment for the measurement of the distance R) is obtained as below; equation (1) is derived with respect to time and we eliminate $\dot{y}$ between equation (1) and equation (3); after that we eliminate $\dot{\psi}$ between the new equation and equation (5); we obtain successively:

$$\dot{\lambda} = \frac{57.3}{R}\dot{y} - \frac{57.3}{R^2}\dot{R}y \cong \frac{57.3}{R}\dot{y} \overset{(3)}{=} \frac{57.3}{R}\cdot\frac{V_0}{57.3}\Delta\psi. \quad (9)$$

Thus, we have:

$$\dot{\lambda} \cong \frac{V_0}{R(t)}\Delta\psi = \frac{V_0}{R}\cdot\frac{1}{s}\Delta\dot{\psi} = \frac{V_0}{R}\dot{\psi} \overset{(5)}{=} \frac{g}{R}\varphi. \quad (10)$$

By elimination of the roll angle φ between (10) and (5), and taking into consideration that the distance R is appreciatively constant during the dynamic regimes of the physical variables in Fig. 3, it follows:

$$\Delta\psi_c \approx \Delta\lambda = \lambda. \quad (11)$$

The control law of $\Delta\psi_c$ is chosen P.I.D. type (proportional – integral – derivative) so that $\Delta\lambda = \lambda = \lambda_c = 0$. Taking into account that $\Delta\psi$ must not be calculated as in Fig. 3 and it must be measured by using a direction gyro, an ideal integrator is placed, like in Fig. 2 too, on the direct way of the subsystem with the input $\Delta\psi_c$ and the output $\Delta\psi$. Thus, in steady regime we write:

$$\Delta\psi_c = \Delta\psi = \varphi_c = \varphi = \omega_{x_c} = \omega_x = y = \dot{y} = 0. \quad (12)$$

III. DYNAMICS OF THE AIRCRAFT IN LATERAL PLANE

For the orientation and stabilization of the aircrafts on the runway direction, the system in Fig. 3 may be used. For the study of the system dynamics, we consider an aircraft Charlie–1 [1].

The equations of the aircraft lateral movement are [5]:

$$\begin{aligned}
\Delta\dot{V}_y &= Y_v\Delta V_y - V_{x0}\Delta\omega_z + g\cos\theta_0\Delta\varphi + Y_{\delta_d}\Delta\delta_d,\\
\Delta\dot{\omega}_x &= L'_v\Delta V_y + L'_p\Delta\omega_x + L'_r\Delta\omega_z + L'_{\delta_e}\Delta\delta_e + L'_{\delta_d}\Delta\delta_d,\\
\Delta\dot{\omega}_z &= \mathrm{N}'_v\Delta V_y + \mathrm{N}'_p\Delta\omega_x + \mathrm{N}'_r\Delta\omega_z + \mathrm{N}'_{\delta_e}\Delta\delta_e + \mathrm{N}'_{\delta_d}\Delta\delta_d,\\
\Delta\dot{\varphi} &= \Delta\omega_x + \tan\theta_0\cdot\Delta\omega_z,\\
\Delta\dot{\psi} &= \frac{\Delta\omega_z}{\cos\theta_0}.
\end{aligned} \quad (13)$$

Ignoring, by notation, the symbol Δ, the state equation which describes the lateral movement of the aircraft is [5], [16]:

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u}, \quad (14)$$

with the state vector $\boldsymbol{x} = [V_y \quad \omega_x \quad \omega_z \quad \varphi \quad \psi]^T$, the command vector $\boldsymbol{u} = [\delta_e \quad \delta_d]^T$, and the matrices A and B of forms:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0\\ a_{21} & a_{22} & a_{23} & a_{24} & 0\\ a_{31} & a_{32} & a_{33} & a_{34} & 0\\ 0 & 1 & \tan\theta_0 & 0 & 0\\ 0 & 0 & 1/\cos\theta_0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} Y_v & 0 & -V_{x0} & g\cos\theta_0 & 0\\ L'_v & L'_p & L'_r & 0 & 0\\ \mathrm{N}'_v & \mathrm{N}'_p & \mathrm{N}'_r & 0 & 0\\ 0 & 1 & \tan\theta_0 & 0 & 0\\ 0 & 0 & 1/\cos\theta_0 & 0 & 0 \end{bmatrix}, \quad (15)$$
$$B = \begin{bmatrix} b_{11} & b_{12}\\ b_{21} & b_{22}\\ b_{31} & b_{32}\\ b_{41} & b_{42}\\ b_{51} & b_{52} \end{bmatrix} = \begin{bmatrix} 0 & Y_{\delta_d}\\ L'_{\delta_e} & L'_{\delta_d}\\ \mathrm{N}'_{\delta_e} & \mathrm{N}'_{\delta_d}\\ 0 & 0\\ 0 & 0 \end{bmatrix}.$$

The elements of the above matrices are calculated with respect to the stability derivates, using the equations [5]:

$$\begin{aligned}
&I_A = \frac{J_{xz}}{J_{xx}}, I_B = \frac{J_{xz}}{J_{zz}}, I' = 1 - I_A I_B,\\
&L'_v = \frac{L_v + I_A\mathrm{N}_v}{I'}, L'_p = \frac{L_p + I_A\mathrm{N}_p}{I'}, L'_r = \frac{L_r + I_A\mathrm{N}_r}{I'},\\
&\mathrm{N}'_v = \frac{L_v I_B + N_v}{I'}, \mathrm{N}'_p = \frac{L_p I_B + N_p}{I'}, \mathrm{N}'_r = \frac{L_r I_B + N_r}{I'},\\
&L'_{\delta_e} = \frac{L_{\delta_e} + I_A N_{\delta_e}}{I'}, L'_{\delta_d} = \frac{L_{\delta_d} + I_A N_{\delta_d}}{I'},\\
&\mathrm{N}'_{\delta_e} = \frac{L_{\delta_e} I_B + N_{\delta_e}}{I'}, \mathrm{N}'_{\delta_d} = \frac{L_{\delta_d} I_B + N_{\delta_d}}{I'},
\end{aligned} \quad (16)$$

where

$$
\begin{aligned}
&L_v = \frac{1}{J_{xx}}\frac{\partial M_x}{\partial V_y},\ L_p = \frac{1}{J_{xx}}\frac{\partial M_x}{\partial \omega_x},\ L_r = \frac{1}{J_{xx}}\frac{\partial M_x}{\partial \omega_z},\\
&L_{\delta_e} = \frac{1}{J_{xx}}\frac{\partial M_x}{\partial \delta_e},\ L_{\delta_d} = \frac{1}{J_{xx}}\frac{\partial M_x}{\partial \delta_d},\\
&\mathrm{N}_v = \frac{1}{J_{zz}}\frac{\partial M_z}{\partial V_y},\ \mathrm{N}_p = \frac{1}{J_{zz}}\frac{\partial M_z}{\partial \omega_x},\ \mathrm{N}_r = \frac{1}{J_{zz}}\frac{\partial M_z}{\partial \omega_z},\\
&\mathrm{N}_{\delta_e} = \frac{1}{J_{zz}}\frac{\partial M_z}{\partial \delta_e},\ \mathrm{N}_{\delta_d} = \frac{1}{J_{zz}}\frac{\partial M_z}{\partial \delta_d};
\end{aligned}
\tag{17}
$$

M_x, M_z are the components of the aircraft resultant moment along the axes Ox and Oz (the longitudinal and vertical axes), J_{xx}, J_{zz} – axial inertia moments with respect to axes Ox and Oz, J_{xz} – planar inertia moment with respect to the aircraft vertical plane Oxz.

For the Charlie-1 aircraft, the coefficients which interfere in equations (15) and (16) are [1]:

$$
\begin{aligned}
&V_0 = 67\,[\mathrm{m/s}], Y_v = -0.089\,[\mathrm{deg/m\cdot s}],\\
&L'_v = -1.33\,[\mathrm{deg/m\cdot s}], L'_p = -0.98\,[1/\mathrm{s}],\\
&L'_r = 0.33\,[1/\mathrm{s}], \mathrm{N}'_v = 0.17\,[\mathrm{deg/m\cdot s}],\\
&\mathrm{N}'_p = -0.17\ [1/\mathrm{s}], \mathrm{N}'_r = -0.217\ [1/\mathrm{s}],\\
&Y_{\delta_d} = 1\left[\mathrm{m/deg\cdot s^2}\right], L'_{\delta_e} = 0.23\left[1/\mathrm{s}^2\right],\\
&L'_{\delta_d} = 0.06\left[1/\mathrm{s}^2\right], \mathrm{N}'_{\delta_e} = 0.026\left[1/\mathrm{s}^2\right],\\
&\mathrm{N}_{\delta_d} = -0.15\left[1/\mathrm{s}^2\right].
\end{aligned}
\tag{18}
$$

To express the sideslip angle (β) as a state variable, we use the relationship:

$$
\beta = \frac{V_y}{V_{x_0}} \cong \frac{V_y}{V_0} \tag{19}
$$

and we obtain the equations (4) or the state equation (14) with the matrices A and B of forms [1]:

$$
A = \begin{bmatrix} -0.089 & 0 & -67 & 9.81 & 0 \\ -1.33 & -0.98 & 0.33 & 0 & 0 \\ 0.17 & -0.17 & -0.217 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix},\ B = \begin{bmatrix} 0 & 1 \\ 0.23 & 0.06 \\ 0.026 & -0.15 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}. \tag{20}
$$

IV. SIMULATION SIMULATIONS

Using the Matlab/Simulink environment we tested the automatic command system for the flight direction control with radio navigation system and DME (Fig. 3).

The transfer function of the direction controller in Fig.3 is:

$$
H_c(\mathrm{s}) = \frac{\Delta\psi_c(\mathrm{s})}{\Delta\lambda(\mathrm{s})} = k_c\left(1 + \frac{1}{T_i \mathrm{s}} + T_d \mathrm{s}\right), \tag{21}
$$

while the transfer function of the servo – aileron is:

$$
\frac{\delta_e(\mathrm{s})}{\delta_{e_c}(\mathrm{s})} = \frac{1}{T_e \mathrm{s} + 1}. \tag{22}
$$

The parameters that interfere in the above two equations and in the block diagram of the system (Fig. 3) are:

$$
\begin{aligned}
&T_e = 2\,[\mathrm{s}], T_i = 41\cdot 10^3\,[\mathrm{s}], T_d = 6.58\,[\mathrm{s}], k_\psi = 0.6,\\
&k_c = 4.1, k_\varphi = 200, k_{\dot\varphi} = 800\,[\mathrm{deg/(deg/s)}],\\
&k_\lambda = 1\,[\mathrm{V/deg}], R_0 = R(0) = 6700\,[\mathrm{m}],\ V_0 = 67\,[\mathrm{m/s}].
\end{aligned}
\tag{23}
$$

The model of the aircraft lateral movement has the general form (14) with the matrices A and B of form (20). To obtain the time function $y(t)$ and $\dot y(t)$, we used the relationship [1]:

$$
\dot y = \frac{V_0}{57.3}\Delta\psi. \tag{24}
$$

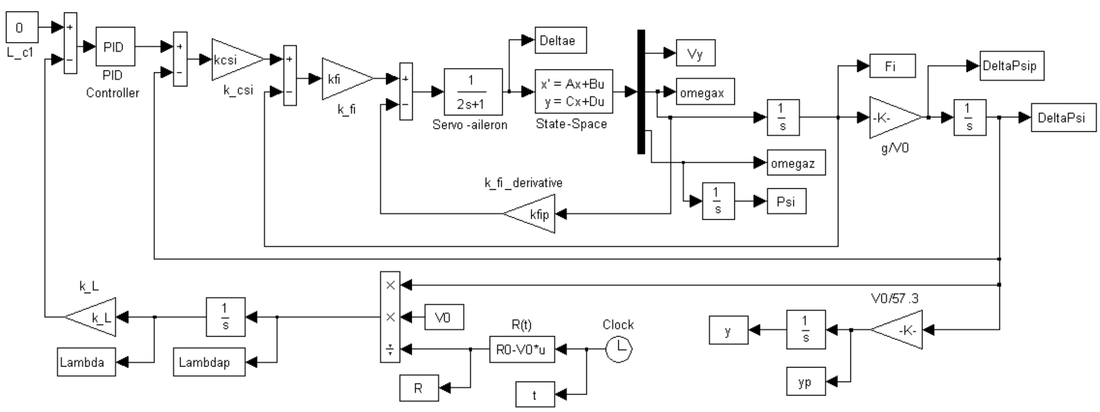

Figure 4. Matlab/Simulink model for the system in Fig. 3

To obtain the time variations of the main variables which characterize the direction control system, the Matlab/Simulink model from Fig. 4 has been used. This Matlab/Simulink model is the representation of the system from Fig. 3 in Matlab environment.

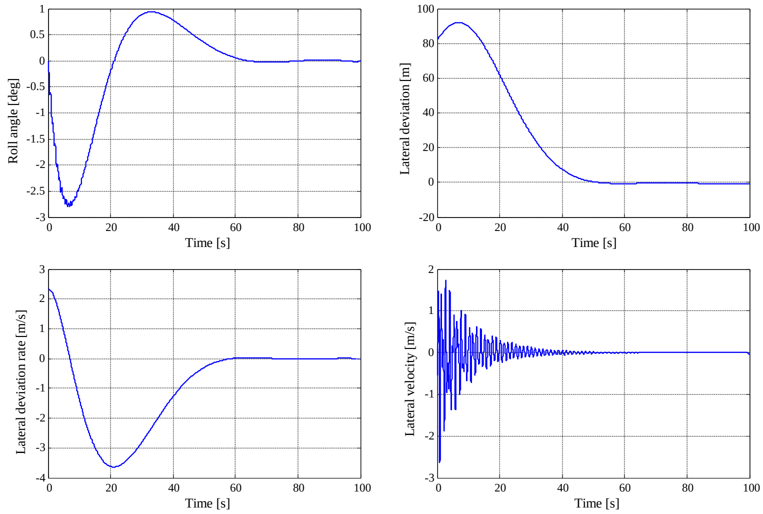

Figure 5. Time variation of the variables $\varphi, y, \dot{y}, V_y$

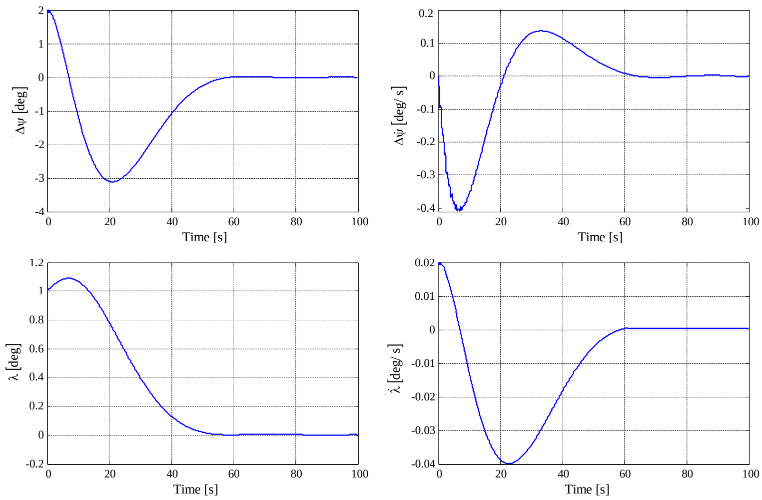

Figure 6. Time variation of the variables $\Delta\psi, \Delta\dot{\psi}, \lambda, \dot{\lambda}$

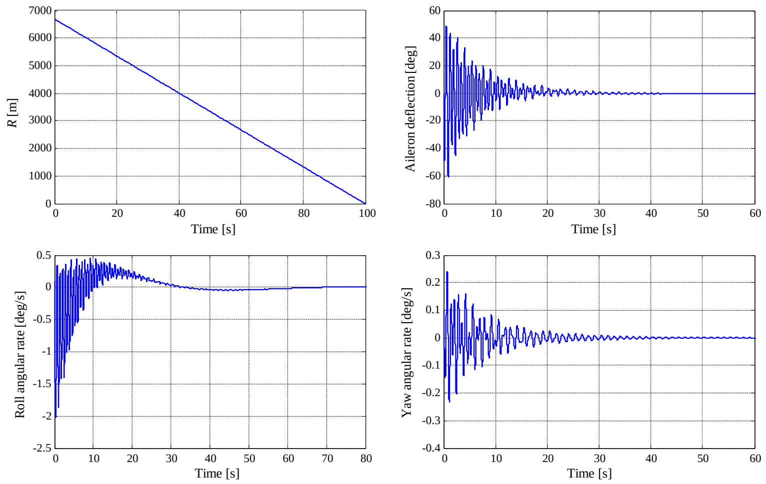

Figure 7. Time variation of the variables $R, \delta_e, \omega_x, \omega_z$

In Fig. 5-7 we represented the time variations of the main variables which characterize the command system for the flight direction control: $\varphi, y, \dot{y}, V_y$ (Fig. 1), $\Delta\psi$, $\Delta\dot{\psi}, \lambda, \dot{\lambda}$ (Fig. 2), and $R, \delta_e, \omega_x, \omega_z$ (Fig. 3), respectively. y denotes the aircraft lateral deviation with respect to the radio marker direction, $\dot{y}$ is the lateral deviation rate, and V_y – the aircraft lateral velocity. As one can see in Fig. 5, all these variables tend to zero; that means that the system in Fig. 3 cancels the aircraft lateral deviation with respect to the radio marker direction and the aircraft direction is now the direction imposed by the radio marker. The transient regime takes about 40-60 seconds, but this is not a problem, because the direction control system begins to work long time before the starting of the landing process. For this aircraft type (Charlie-1), the first stage of the landing process (the glide slope descend) begins when the aircraft is 30 m above the ground, while the second stage of the landing process (the flare maneuver) begins at 3 m above the ground.

In Fig. 6 we notice that the errors $\Delta\psi$, $\Delta\dot{\psi}$ tend to zero in the interval of 60 seconds; the system cancels the angle λ (the angle measured in horizontal plane between the aircraft longitudinal axis and the radio marker direction) and its derivative $(\dot{\lambda})$. Thus, in steady regime, we note that $\Delta\psi = \Delta\dot{\psi} = \lambda = \dot{\lambda} = y = \dot{y} = 0$; the distance between the aircraft and the radio marker (R) becomes zero in about 100 seconds – Fig. 7. Because now the aircraft direction is the desired one, the pilot must not deflect the ailerons and the rudder any more; thus, these deflections are zero $(\delta_e = \delta_d = 0)$, and, as a consequence, the roll angle, the roll angular rate, and the yaw angular rate become zero – Fig. 7.

V. Conclusion

The landing process is simplified if the aircrafts movement in lateral plane is made without errors (deviation of the aircrafts from the runway direction is zero). That is why the systems for the automatic command (control) of the flight direction are very important. The landing approach is considered to be precise if the deviation of the aircraft direction does not overcome 20-30 angular minutes and the deviation with respect to the glide slope is less than 10-15 angular minutes.

The system (autopilot) presented in this paper may be used, with good results, to the automatic control of the aircrafts flight direction before the landing process. The paper authors validated the obtained autopilot by numerical simulations in Matlab/Simulink and obtained a lot of time characteristics (time variations of the variables involved in the approach landing process).

The authors intend in the future to project an automatic pilot, based on dynamic inversion or on the backstepping method, for the whole landing process.

Acknowledgment

This work was supported by CNCSIS-UEFISCSU, project PN II-RU, No.1/28.07.2010, "High-precision strap-down inertial navigators, based on the connection and adaptive integration of the nano and micro inertial sensors in low cost networks, with a high degree of redundance", code TE_102/2010.

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