

Evaluation of the Dynamic Characteristics of Aircraft during Landing in Crosswinds

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Abstract – This article summarizes the results of aircraft lateral drift parameter estimation. The lateral drift of an aircraft may occur in extreme and dangerous situations when the aircraft lands in crosswind conditions. Such a situation is developing with great dynamics in a small period of time. Within seconds, the aircraft can drastically change the flight path or position. The article highlights the results obtained in a calculation made during the flight phase of the aircraft landing in crosswind.

Keywords – Bank angle, crosswind, flight safety, tail fin.

I. INTRODUCTION

The flight of an aircraft can be considered successfully completed only when it has smoothly decelerated to a halt on the runway lane [1].

In practice, it can be seen that this is not always the case. Difficult and dangerous situations after touching the runway become accident factors in civil aviation. Most of them are “hard” landings of aircraft skid in outside the runway safety lanes [2].

The security lane is a specially prepared area along the runway and is intended for take-off and landing to ensure safety [3]. As a rule, “hard” landings end for passengers not only without incident but also without aviation accidents with severe consequences and fatalities.

The incidents that have recently occurred only in Russia prove the existence of this problem [4], [5]:

- On 12 February 2013 in Rostov-on-Don Airport “Siberia” aircraft A319 slipped to the extreme security zone;
- On 22 January 2013 in Chelyabinsk Airport “Ural Airlines” aircraft A321 slipped outside the runway line after the landing over the boundary lights;
- On 20 January 2013 in Chelyabinsk Airport “Aeroflot” aircraft A320 ran out with the front landing gear over the left outside lane boundary lights;
- On 17 January 2013 in Moscow Domodedovo Airport “Transaero” aircraft B737 released the runway lane and slipped outside of it;
- On 09 January 2013 in Saransk Airport “Mordovia Airlines” aircraft AN24 slipped out of the runway during the run-up for take-off to the left side safety zone up to 30 meters, in addition the aircraft spun 160 degrees;
- On 29 December 2012 in Moscow Vnukovo Airport “Red Wings” aircraft TU204 roll out of the runway security zone;
- On 20 December 2012 in Tolmachevo Airport “Red Wings” aircraft TU204 slipped behind the safety zone;
- On 12 February 2012 in Nizhnekamsk Begishevo Airport “Aero Bars” aircraft CRJ200 rolled out of the security zone;
- On 12 January 2012 in Rostov-on-Don Airport “Yakutia” aircraft B737–800 slipped in excess of 80 meters above the take-off threshold on runway;
- On 30 November 2012 in Ulyanovsk Baratayevka Airport “Utair” aircraft ATR72 slipped outside the runway;
- On 21 November 2012 in Deputatskiy Airport polar airline “Yakutia” aircraft AN26B–100 landed in fog conditions and slipped to the left of the runway zone axis.

This case study shows that such incidents are mainly based on human factor and that it is usually the fault of the crew error. Inaccuracies on the glide path, further already during the landing summed up, as aircraft “hard” landings with its slipping out of the runway [6]. A precursor to this type of incident is insufficient flight skill in keeping the course and trajectory of lanes before the landing stage [7]. Paying too much attention to landing retention rate (path route) and increasing drift angle, the pilot usually loses control over glide characteristics: pitch angles, supply air speed, engine operation mode and mainly over the sink rate [8].

As the vertical velocity is the main parameter of approach, pilots are seeking for possibilities to reduce vertical speed to a minimum before the runway contact. If the pilot fails, the descent is rigid [9]. If the vertical speed is not maintained within the normal range, it is a prerequisite for the supply air rate loss and ultimately the aircraft is slipping out of the runway.

At the landing with a crosswind, the pilot can misinterpret the landing position because if the aircraft is rotated by the angle of their migration, the runway lane cannot project directly in front of the pilot's view (usually it happens at the minimum acceptable landing weather), but on the one side of the plane, which depends on the lateral wind direction [10]. At the aircraft's flight path imbalance usually results in the pilot's effort to fill planes parallel to the course of landing strip axis [11]. If the crew clarify their error too late and try to correct it immediately prior to the runway line, it leads to a “hard” landing of the aircraft and slipping outside the runway lane.

In case of landing with a crosswind the aircraft arrives the lane with the security angle in order to keep track of runway lane. When the path of the period remains only 7 to 10 seconds before touching the runway, the pilot removes the safety angle with the help of the directional rudder, therefore leading the aircraft to the lateral movement parameter changes [12]. This paper analyses the results of theoretical calculations on the lateral motion of the aircraft parameters, which eliminates the rudder angle of the steering axis manoeuvres before landing a counterforce in order to maintain the trajectory and the desired lateral direction within the acceptable range. [13]

II. RESEARCH ON AIRCRAFT LANDING WITH A CROSSWIND

Negative compliance with the centre line is being wound up by directional rudder assistance in cases when there is crosswind, aircraft cannot line up the runway centre and only 7 to 10 seconds are left before contact with the runway or before landing [14]. Such a manoeuvring method suggests the change of lateral movement parameters. In this situation, the aircraft has an increasing angle of bank and the aircraft departs from the landing path bar axis. The danger is that the angle of bank and the offset from the landing zone axis can move beyond the permissible limits. In order to prevent bank and offset from the axis, the method of lateral control, the required deficiency is chosen for specific landing conditions (atmospheric conditions, aerobatic style), as well as the dynamic behaviour of the same lateral direction of aircraft movement.

Therefore it follows that the potential effectiveness of the aircraft position defines the aircraft landing options for the crosswind situation. It is important to know the parameters characterizing the changes in the lateral movement of the aircraft when analysing the situation in a normal landing. The aircraft is controlled by the direction rudder and the necessary effectiveness lateral direction of motion control in order to maintain these parameters within acceptable limits (see Fig. 1).

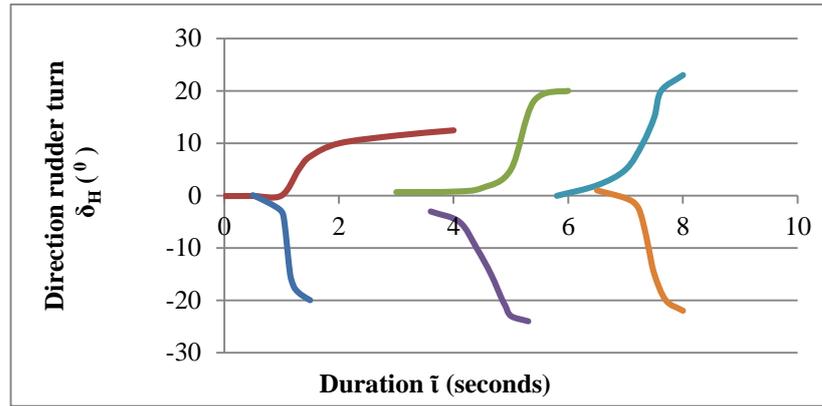


Fig. 1. Nature of directional rudder manoeuvres obtained from test flights.

The motion control of a common scene at the control manoeuvre effect is described to a common coordinate system and is as follows (1):

$$\begin{aligned}
 mV_o \frac{d\beta}{dt} + mV_o \frac{d\psi}{dt} &= Z_B \\
 I_x \frac{d\omega_x}{dt} - I_{xy} \frac{d\omega_y}{dt} &= M_{XB} + \Delta M_{x0} = M_x \\
 I_y \frac{d\omega_y}{dt} - I_{xy} \frac{d\omega_x}{dt} &= M_{yB} + \Delta M_{y0} = M_y
 \end{aligned} \quad (1)$$

where β – slip angle;
 ψ – flight route angle;
 ω_x – angular velocities in x direction;
 ω_y – angular velocities in y direction;
 M – mass of the aircraft;
 I_x, I_y, I_{xy} – moments of inertia;
 Z_B – side force;
 M_{XB} – heel torque;
 M_{yB} – flight path torque.

The determination of the run-off lateral direction is accompanied by a kinematic equation (2):

$$\dot{Z}_D = V_o(\beta - \psi) \quad (2)$$

The required aileron rotation is set with the help of manoeuvrability characteristics. In addition, the aileron angle of the rudder wheel land power must not exceed the permissible limits (3):

$$\begin{aligned}
 \delta_3 &= \gamma / \left(\frac{d\omega_x}{d\delta_3} \right) + \left(\frac{dP_3}{d\gamma} / \frac{dP_3}{d\delta_3} \right) \gamma \leq \delta_{max} \\
 P_3 &= \left(\frac{dP_3}{d\omega_x} \right) \gamma + \left(\frac{dP_3}{d\gamma} \right) \gamma \leq P_{3max}
 \end{aligned} \quad (3)$$

After linearization, a system of equations (4) is obtained and it allows to specify the aileron rotation positions at different rudder angles:

$$\begin{bmatrix} \lambda + n_{z\beta} + n_{z\gamma} - \lambda \\ n_{x\beta}\lambda(\lambda + n_{xY})n_{x\phi}\lambda \\ n_{y\beta}n_{yY}\lambda\lambda(\lambda + n_{x\phi}) \end{bmatrix} \begin{Bmatrix} \beta \\ \gamma \\ \psi \end{Bmatrix} = \begin{Bmatrix} 0 \\ n_{x\delta H} \\ n_{y\delta H} \end{Bmatrix} \{ \delta_H \} \quad (4)$$

$$n_{z\beta} = -\frac{c_{z\beta}}{\dot{\tau}}; \quad n_{z\gamma} = \frac{g}{V_o}; \quad n_{xY} = -\frac{2m\dot{\omega}_x}{\dot{\tau}^2} - n_{xI}n_{yY}; \quad n_{xI} = \frac{I_{xy}}{I_x \left[1 - \frac{I_{xy}^2}{I_x I_y} \right]} \quad (5)$$

$$n_{x\dot{\omega}} = -\frac{2m_x^{\dot{\omega}x}}{\bar{I}_x^2} - n_{xI}n_{y\dot{\omega}}; n_{x\beta} = -\frac{4m_x^\beta}{\bar{I}_x^2 \bar{I}_x^2} \mu_\beta - n_{xI}n_{y\beta}; n_{yI} = \frac{I_{xy}}{I_y \left[1 - \frac{I_{xy}^2}{I_x I_y} \right]} \quad (6)$$

$$n_{yY} = -\frac{2m_y^{\dot{\omega}y}}{\bar{I}_y^2} - n_{yI}n_{xY}; n_{y\dot{\omega}} = -\frac{2m_y^{\dot{\omega}y}}{\bar{I}_y^2} - n_{yI}n_{y\dot{\omega}}; \bar{I}_x^2 = \frac{4I_x}{ml^2}; \bar{I}_y^2 = \frac{4I_y}{ml^2} \quad (7)$$

$$n_{y\beta} = -\frac{4m_y^\beta}{\bar{I}_x^2 \bar{I}_x^2} \mu_\beta - n_{yI}n_{x\beta}; n_{y\delta H} = \frac{4m_y^{\delta H}}{\bar{I}_y^2} \mu_\beta + n_{yI}n_{x\delta H}; \mu_\beta = \frac{2m}{\rho_0 S l}; \bar{I}_y = \frac{2m}{\rho_0 S V_0} \quad (8)$$

As the aircraft controls the motion with the direction rudder, function $(1-e^{pt}) \delta_H$ is chosen. It describes the relation of direction actual steering manoeuvres with sufficient accuracy (see Fig. 2).

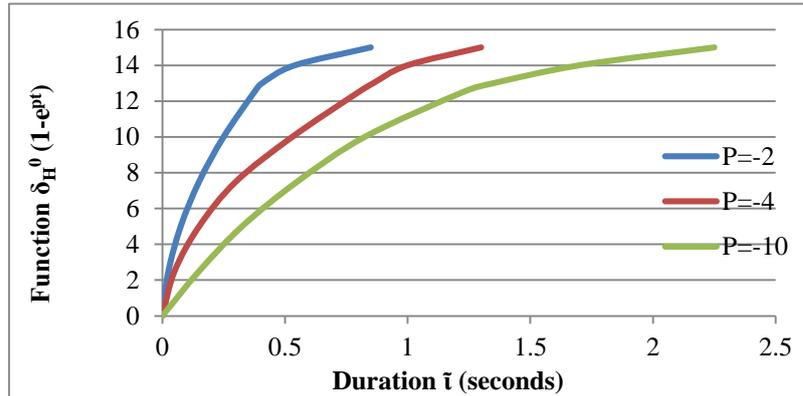


Fig. 2. Function $(1-e^{pt}) \delta_H$ changes depending on the time and the taken force applied to the rudder wheel.

III. CALCULATED RESULTS

The calculations are performed for a TU-134 aircraft [15]. Aerodynamic and performance characteristics are given in Table I.

TABLE I
AERODYNAMIC AND PERFORMANCE CHARACTERISTICS OF TU-134 AIRCRAFT

G	V_0	α	l	S
40 T	257 km/h	6°	29 m	115 m ²
c_z^β	m_x^β	$m_x^{\dot{\omega}x}$	m_y^β	$m_y^{\dot{\omega}x}$
-0.144	-0.0345	-0.5; -0.336	-0.0031	0.07
$m_y^{\delta H}$	$m_x^{\delta H}$	$m_y^{\dot{\omega}y}$	$m_x^{\dot{\omega}y}$	I_x
-0.001	-0.0002	-0.16	-0.31	72.5*10 ⁶
I_{xy}	r_x^x	r_x^2	τ	μ_δ
11.4*10 ⁶	0.0845	0.297	7.95	19.6
n_{xI}		n_{yI}		I_y
0.158		0.045		255*10 ⁶

where G – weight;
 V_0 – speed;
 α – angle of bank;
 l – length;
 S – square;
 c_z^β – lift coefficient;
 τ – duration;

μ_δ – flight path angle;
 $m_x^\beta, m_y^\beta, m_x^{\omega_x}, m_y^{\omega_x}, m_y^{\delta H}, m_x^\delta, m_y^{\omega_y}, m_x^{\omega_y}$ – moments of angular velocities in x and y directions;
 r_x, r_x^2 – accelerations;
 n_{xI}, n_{yI} – overload factors;
 I_x, I_{xy}, I_y – the moments of inertia.

The ultimate version of the type of aircraft landing manoeuvres will be the ultimate case when the aircraft is implemented in a completely “clean” way according to the movement of the flight route. In this case, there is no bank, for example, because it is eliminated with the help of ailerons. The lateral movement fluctuations of the parameters in this case show (see Figs. 3 and 4) that in this time interval the flight path angle turns into the slip angle and run-off during this period does not have time to develop. For the small turns of the directional rudder wheel, manoeuvring to a minimum has also smaller angle β and ψ . Changes in parameter P in the range of -2 to -10 practically do not affect the result. However, neither β nor ψ in the selected range has no time to pass on the values under the steady state and, apparently, after landing on the runway will continue to increase in value.

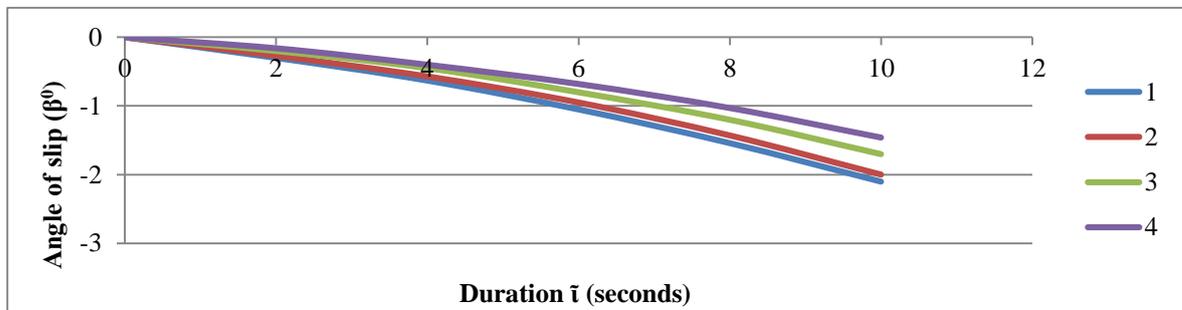


Fig. 3. Slip angle changes for “clean” movement along the flight path.
 1 – $\beta^0 = 200, P = -10$; 2 – $\beta^0 = 200, P = -2$; 3 – $\beta^0 = 150, P = -10$; 4 – $\beta^0 = 150, P = -2$

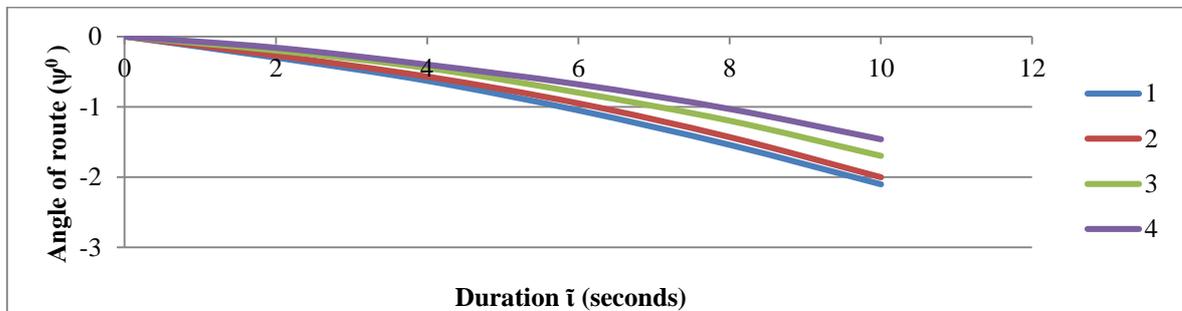


Fig. 4. Flight route angle changes for “clean” movement along the flight path.
 1 – $\beta^0 = 200, P = -10$; 2 – $\beta^0 = 200, P = -2$; 3 – $\beta^0 = 150, P = -10$; 4 – $\beta^0 = 150, P = -2$

Calculated results for the case in which management takes place without the use of flaps is shown in Figs. 5, 6, 7 and 8.

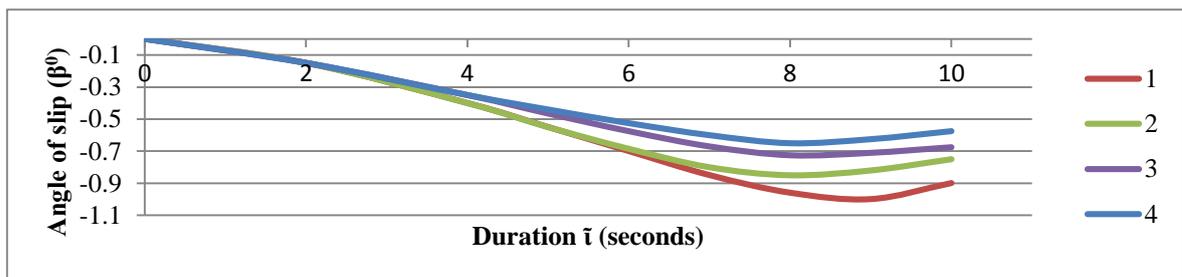


Fig. 5. Changes in the slip angle made with the rudder wheel.
 1 – $\delta_V = 20^0, m_x^{\omega_x} = -0.5$; 2 – $\delta_V = 20^0, m_x^{\omega_x} = -0.556$; 3 – $\delta_V = 15^0, m_x^{\omega_x} = -0.5$; 4 – $\delta_V = 15^0, m_x^{\omega_x} = -0.556$

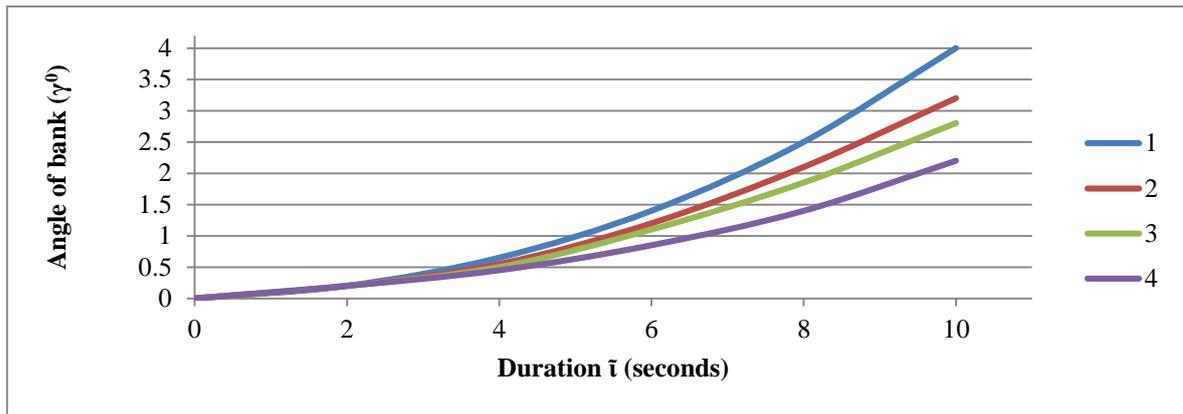


Fig. 6. Changes in the bank angle made with the rudder wheel.

1 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.5$; 2 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.556$; 3 - $\delta_V = 15^\circ$, $m_x^{\omega_x} = -0.5$; 4 - $\delta_V = 15^\circ$, $m_x^{\omega_x} = -0.556$

It can be seen in figures that at the material time the angle β^0 manages to a reachable value; the time to achieve this value depends on the bank damp in the flight path angle continues to grow, therefore side run-off increases, as shown in Fig. 8, at the first interval landing has not run-off impact.

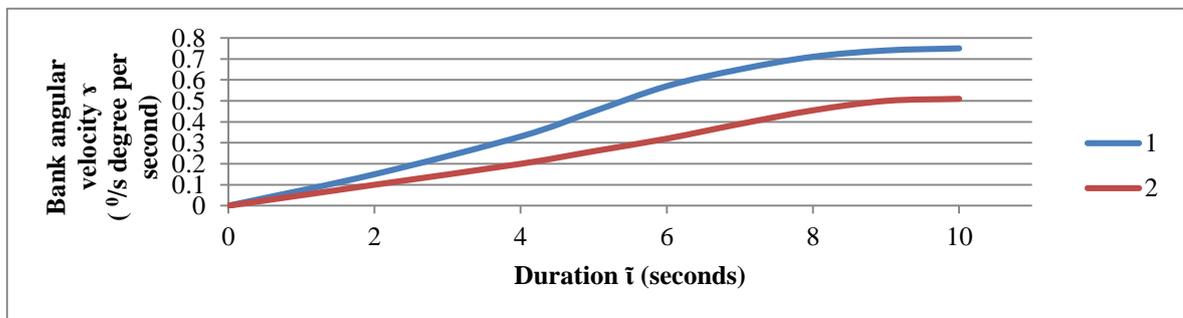


Fig. 7. Bank angular velocity changes made with the directional rudder wheel.

1 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.336$; 2 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.5$

The angle of bank, as it increases particularly at the end, depends on the established angular velocity arrangement. In addition, the largest values correspond to the smallest values of the angle of bank.

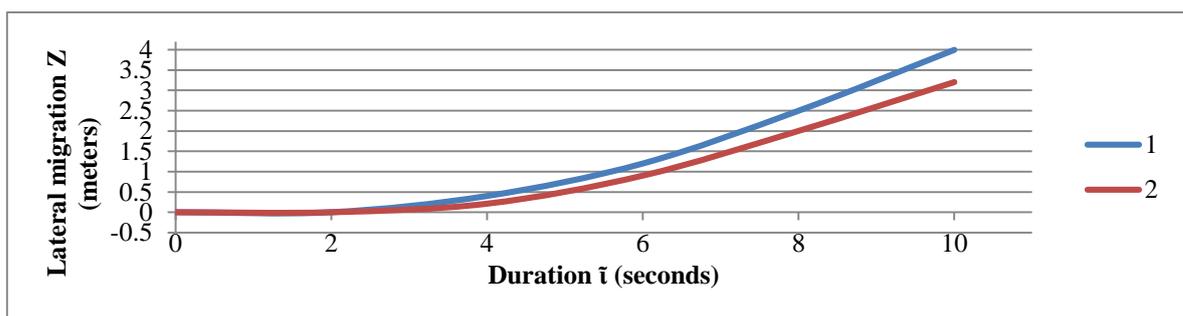


Fig. 8. Lateral migration changes made with the directional rudder wheel.

1 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.336$; 2 - $\delta_V = 20^\circ$, $m_x^{\omega_x} = -0.5$

The listed results state that the prevention of lateral migration or its retention within the acceptable range is required to get it with the rotation of the directional rudder to manoeuvre with the flaps to create the angle of bank, with the opposite direction of the torque that develops in the slip angle.

The results of calculating such an event are shown in Figs. 9, 10, 11 and 12. It can be seen that the flight path retention and slipping, during the selected time, are changing and the greatest value is observed when the aircraft is operated by the ailerons. In addition, the obtained angle β^0 is a stabilized value. Practically, the angular change does not have any value in the first interval of the

bank. However, if the liquidation period of migration angle is late, the growth rate can be brought in line with the speed if the landing takes place without ailerons. In addition, the bank moment occurs while the aircraft touches the runway lane with the landing gears. This bank must be eliminated by using other means such as manoeuvring with the direction rudder because the ailerons are fully exhausted. The same can be said in respect of lateral run-off (migration) Z (see Fig. 11 and Fig. 12). These figures depict the static values of the desired turns of ailerons in order to remove the bank depending on the aileron manoeuvring inception after turning the direction rudder wheel. The calculations show that 10 seconds are required for aileron rotation: $\delta_E = 10^0$.

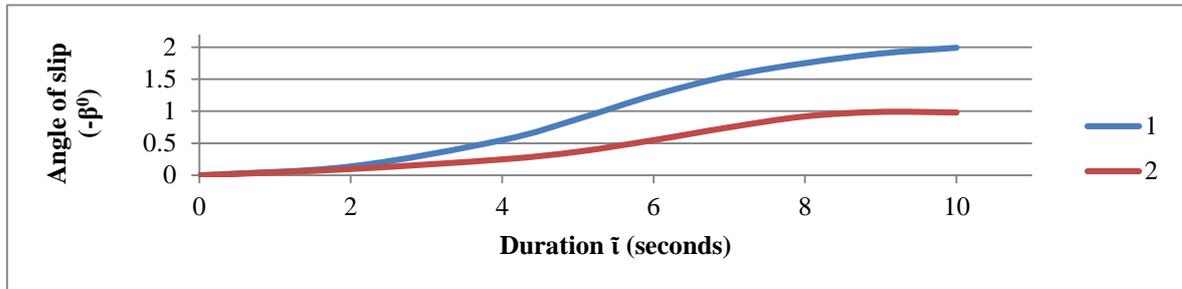


Fig. 9. Dependence of slip angle changes on time.
 1 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 15^0$; 2 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 0^0$

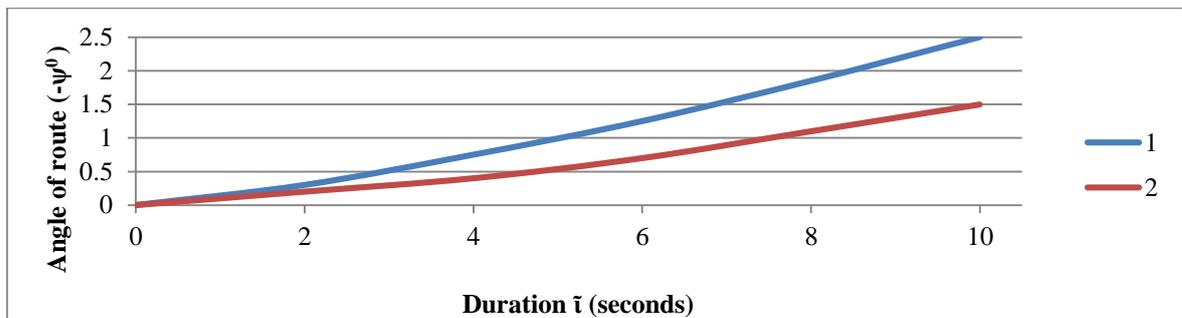


Fig. 10. Dependence of route angle changes on time.
 1 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 15^0$; 2 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 0^0$

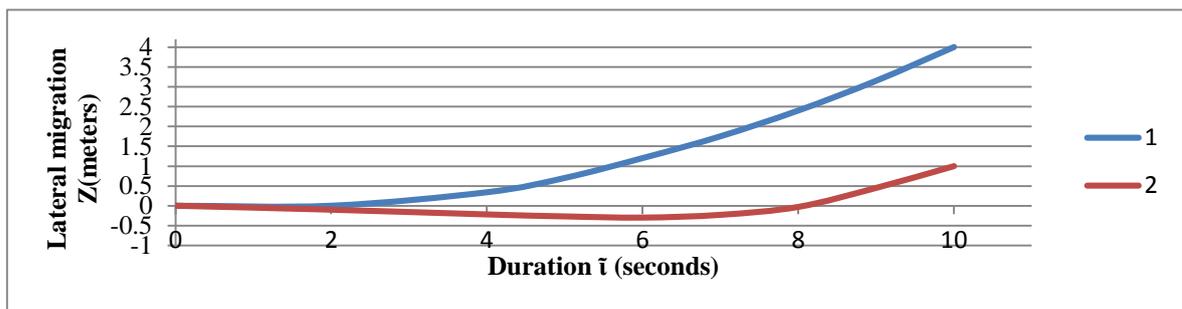


Fig. 11. Lateral migration.
 1 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 15^0$; 2 – $\delta_H = 20^0$, $m_x^{\omega x} = -0.5$, $\delta_E = 0^0$

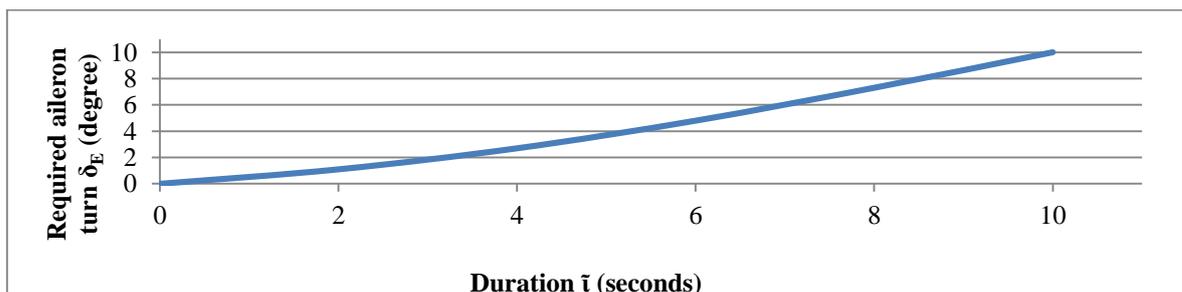


Fig. 12. Dependence of the required aileron rotation on the turning moment of tail fin rudder manoeuvre.

IV. CONCLUSION

1. In order to eliminate the angle of migration from the runway centre line while turning the direction rudder, it is also necessary to turn ailerons to the same extent that allows 5÷7 seconds to keep an aircraft without any impact of the bank angle and lateral migration.

2. If the time required for touching the runway is greater than the time provided as a result of turning the direction rudder and flaps, the aircraft touches the runway with a substantial bank angle and lateral migration. In order to eliminate the bank angle and lateral migration, it is necessary to manoeuvre with the direction rudder because the aileron movement can be fully exhausted.

3. The slip angle at the moment of touching can reach a stable value but the flight path angle still can continue to grow before the aircraft lands with a small angle of migration.

4. If the manoeuvre of ailerons is late in relation to the turn of the direction rudder, additional turning of ailerons is required.

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