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SIMULATION OF HELICOPTER BOUNDARY MANEUVERS OF OBSTACLE AVOIDANCE WITH PREDICTED CONTROL FUNCTION

JAROSŁAW STANISŁAWSKI

New Technology Center, Aircraft Design Department, Institute of Aviation, al. Krakowska 110/114, 02-256 Warsaw, Poland, jaroslaw.stanislawski@ilot.edu.pl

Abstract

Paper presents a simplified method of a simulation of a helicopter controlled flight applied in a program defining an execution of two versions of an obstacle avoidance maneuver, a vertical jump and a horizontal S-turn. Considering the operational limitations of a helicopter, the control function required for maneuver is determined in an iteration process. The flight path for an avoidance maneuver is tailored to pass within the limits of a tolerance strip.

Keywords: helicopter, maneuver, simulation.

1. INTRODUCTION

Helicopter operations often require to perform tasks at a low altitude, which generates a potential risk of collision with terrain obstacles. Due to the height, the following types of flights near ground can be defined: low flights, terrain contour and NOE flights (Nap of the Earth). A flight is regarded as low, when a helicopter flies over the level of the obstacles. The contour flight demands changes of height in accordance with the contour of the terrain. In the NOE flight conditions, a helicopter is kept as close as possible to the ground utilizing the terrain object to hide. Flights at extremely low heights require an increased pilot's attention for simultaneous watching the parameters of flight, for navigation and observation of the terrain. The additional onboard system can help a pilot to make decision to perform a maneuver. Such a system may include an obstacle detection set, a flight parameters measurement unit, a calculation module for a maneuver simulation and a display unit for cueing the control function (Fig. 1). A functionally similar system will be useful on board of an unmanned helicopter generating signals for an autonomic control or cueing the remote operator.

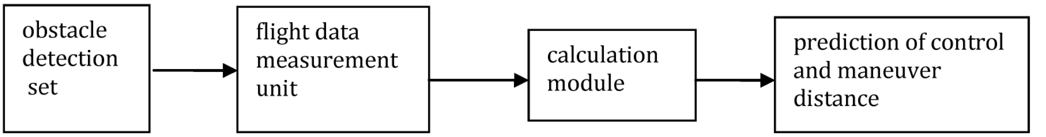

Fig. 1. Scheme of obstacle avoidance system. [Author, 2015]

An effective method of an obstacle detection can improve the safety of helicopter operations at low height flights. Large efforts were made in connection with a detection of power lines. The helicopter system applying laser for wires detection was the subject of American patent made by Koechner [1]. The later articles informed about tests of radar working at millimeter wave band for detection high voltage wires of power lines [2], [3]. The EADS Germany company built the helicopter system HELLAS (Helicopter Laser) [4] for obstacles detection at the range up to 1,000m with a possibility of recognition such obstacles as: wires, trees or pillars. A research program on the system of automatic NOE flights was carried at NASA under the direction of R.Zelenka [5]. The system consisted of: TV cameras, infrared sensors, a radar, a laser and a visualization unit applying a digital map of the terrain connected with flight data measurements. In the case of a collision threat, the system generated a control function to avoid the obstacle.

A progress in a computer technology also influenced the development of unmanned aerial vehicles. One of the desirable features of UAVs is a possibility of flight in autonomy conditions. The article [6] concerns the advantages of the flight control strategy with a possibility of obstacle avoidance based on the actual measurement of a radar mounted on an UAV board instead of using a digital terrain map.

The following paper presents a simplified method of a helicopter flight simulation. A simulation program based on this method can be applied as a part of a calculation module for predicting a flight path and the required control during an obstacle avoidance maneuver. The demand of a short time run of the simulation program leads to an application of a simple model, which includes a point-mass fuselage suspended below the main rotor treated as a disk. Results of a simulation of obstacle avoidance for a vertical jump maneuver and a horizontal S-turn maneuver are presented. The simulations were calculated for data of a light helicopter.

2. MODEL OF HELICOPTER FLIGHT

The model of a helicopter flight enables a simulation of a jump and an S-turn maneuver of obstacle avoidance. The following assumptions are made in the simplified model of helicopter dynamics:

- avoidance maneuver is performed as the plane motion,
- helicopter is treated as point-mass,
- pitch and roll of fuselage are assumed to be equal to pitch and roll angles of the rotor thrust vector,
- collective and cyclic pitch are defined assuming ideal stiffness of the rotor blades,
- avoidance maneuver is divided into basic parts with different control rules,
- the time delay of pilot's reaction to collision threat is assumed,
- maneuver is performed within the limitations of available power, the rotor thrust, the rate of changes of collective and cyclic pitch and limits of roll and pitch of fuselage.

For given initial conditions of the helicopter level flight a simulation program calculates components of the rotor thrust vector, power required for flight and position of control system: collective and cyclic pitch. For the following time steps the acceleration, speed and displacement of a helicopter are defined allowing realization of the maneuver within assumed limitations.

The avoidance maneuver is divided into a few characteristic parts. The initial phase of a maneuver is the level flight during a one second delay of a pilot's reaction when the control system is kept in a constant position. The distance flown by a helicopter is assumed as a part of the distance required for an execution of the maneuver.

In the case of the jump maneuver (Fig. 2) the following phases are taken into account:

- phase of a pull-up with increasing the rotor collective pitch aimed to climb a helicopter, the constant pitch angle of fuselage is assumed;
- time period when, before a climb above an obstacle, the collective pitch is reduced to enable the flight over an obstacle within a permissible strip of height;
- phase after passing the obstacle when the collective pitch is pulled-up again to limit the rate of dive speed and to keep the vertical speed constant with a fixed collective pitch;
- phase of the next collective pitch increase to stop the vertical motion of helicopter at the assumed height above the terrain behind the obstacle.

In the case of the horizontal S-turn the phases of the maneuver are as follows:

- initial phase of the first part of the turn with increasing the roll to the limit value and simultaneously increasing the yaw;
- continuation of the first part turn with increasing the yaw but with simultaneously diminishing the roll to the zero value;
- initial phase of the second turn into the opposite direction reducing the yaw with increasing opposite roll;
- the last phase of simultaneous reducing the helicopter roll and yaw to zero value.

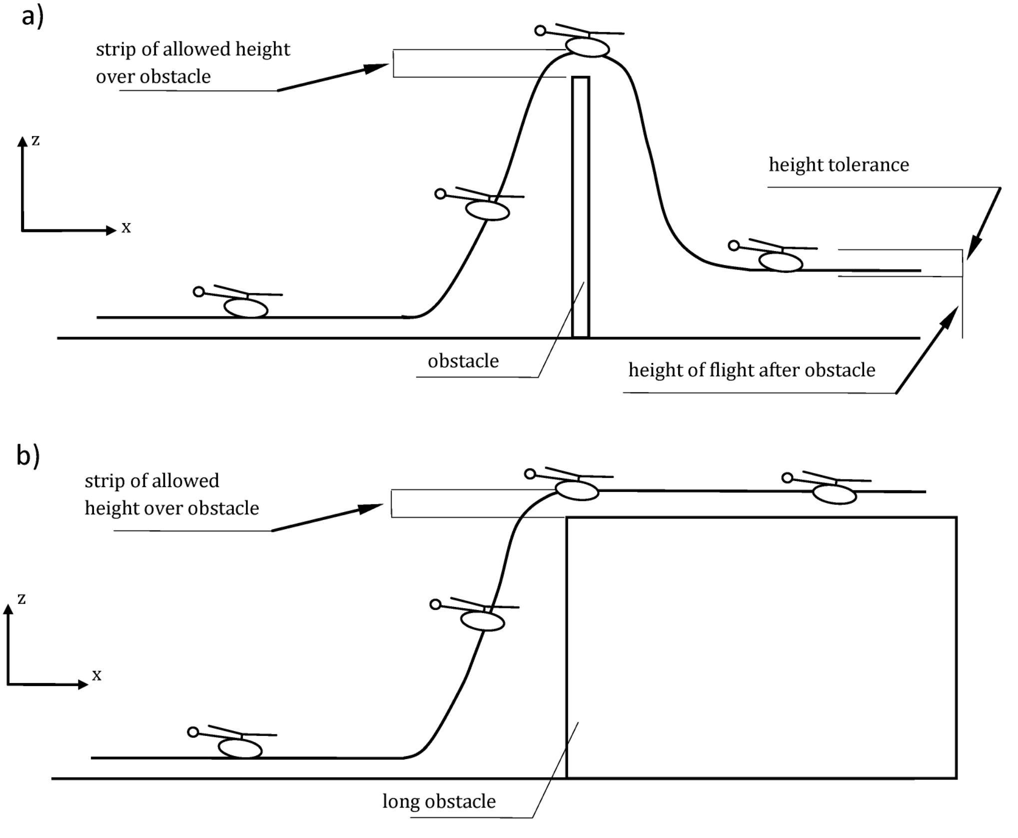

Fig. 2. Scheme of obstacle avoidance jump maneuver:
a) variant with decent after obstacle,
b) variant of flight over long obstacle. [Author, 2015]

For the jump maneuver the pilot's action is modeled indirectly by definition at each time step the increments of helicopter accelerations: horizontal Δa_x and vertical Δa_z , which allow to perform the task at a given phase of a maneuver. In the case of an S-turn at each time step the value of centripetal acceleration Δa_{y_cent} is calculated, which is required for a maneuver execution. For the defined values of accelerations the desired collective and cyclic pitch are calculated.

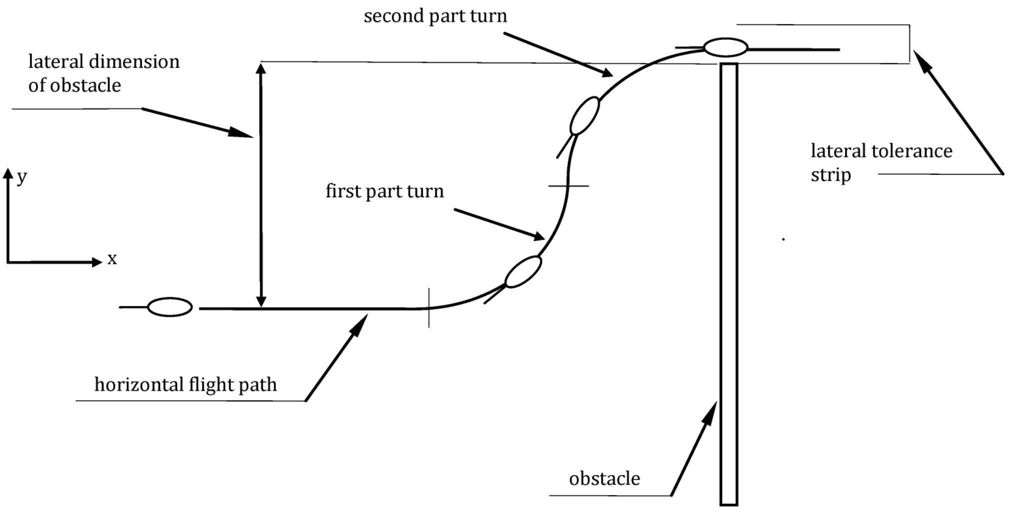

Fig. 3. Scheme of horizontal S-turn obstacle avoidance maneuver. [Author, 2015]

The values of acceleration a_x and a_z possible to realization for a jump and a_{y_cent} for an S-turn depend on the control margins for the following helicopter operational limitations:

- limit of engine maximum power P_{max} ,
- limit of the main rotor thrust T_{limit},
- maximum deflection of the swashplate ϑ_{ymax} - cyclic pitch limit,
- maximum ϑ_{omax} and minimum ϑ_{omin} value of collective pitch,
- maximum rate of change the collective pitch $d\vartheta_o/dt$.

For each kind of limit the increments of accelerations Δa_x and Δa_z (or Δa_{y_cent}) possible to realization are calculated. The corresponding impulses of control (changes of swashplate position) are calculated for each kind of limit. The least impulse among possible for realization is taken as valid for actual time step of helicopter motion. In the time step of a helicopter flight simulation a computing cycle includes procedures calculating the helicopter balance, power required for flight, a position of swashplate (collective and cyclic pitch) and changes of speed and position of the helicopter.

The values of acceleration increments possible to achieve in time step can be calculated by applying the derivatives of thrust $\Delta T/\Delta a_z$, of power $\Delta P/\Delta a_z$ and collective pitch $\Delta\vartheta_o/\Delta a_z$ with respect to acceleration. At moment of time *t* for acceleration a_z the corresponding rotor thrust T, required power P, and collective pitch ϑ_o are calculated. Analogically, for the unitary increment of acceleration

$$a_{z1} = a_z + 1$$

the changed values of thrust T_1, power P_1 and collective pitch ϑ_{o1} can be found. Hence, for unitary impulse of acceleration

$$\Delta a_{z1} = a_{z1} - a_z = 1 \tag{1}$$

the approximate derivatives of thrust, power and collective pitch with respect to acceleration are as follows:

$$\frac{\Delta T}{\Delta a_{z1}} = T_1 - T \quad , \tag{2a}$$

$$\frac{\Delta P}{\Delta a_{z1}} = P_1 - P \quad , \tag{2b}$$

$$\frac{\Delta \vartheta_0}{\Delta a_{z1}} = \vartheta_{01} - \vartheta_0 \quad . \tag{2c}$$

Assuming the linear dependence between increment of acceleration and changes of thrust, power and collective pitch for each kind of limitation, the maximum possible increment of acceleration can be determined:

- for power limit

$$\Delta a_{zP} = \left(P_{\max} - P\right) \cdot \frac{\Delta P}{\Delta a_{z1}} \quad , \tag{3a}$$

- for thrust limit

$$\Delta a_{zT} = \left(T_R - T\right) \cdot \frac{\Delta T}{\Delta a_{z1}} \quad , \tag{3b}$$

- for collective pitch limit

$$\Delta a_{z\vartheta_0} = \left(\vartheta_{0\max} - \vartheta_0\right) \cdot \frac{\Delta \vartheta_0}{\Delta a_{z1}} \quad , \tag{3c}$$

- for collective pitch rate of change limit

$$\Delta a_{z\, d\vartheta/dt} = \frac{d\vartheta_0}{dt} \cdot \Delta t \cdot \frac{\Delta \vartheta_0}{\Delta a_{z1}} \quad . \tag{3d}$$

The least acceleration increment from the values defined in equation (3) provides a control of a helicopter within the accepted limitations. At the next time step $t + \Delta t$ the vertical acceleration of helicopter including influence of a pilot's control is equal

$$a_{z\,t+\Delta t} = a_{z\,t} + \Delta a_{z\,\min} \quad . \tag{4}$$

The horizontal component of the helicopter acceleration is determined as follows:

$$a_x = \left(a_z + g\right) \cdot \sin \varphi_y \quad , \tag{5}$$

where
φ_y – pitch angle of fuselage,
g – acceleration of gravity.

Repeating for the next time steps the calculation cycles of the acceptable accelerations, the flight path and required distance of avoidance maneuver can be determined considering the assumed limitations.

3. JUMP AVOIDANCE MANEUVER

The obstacle avoidance jump maneuver is assumed as a collective pitch pull-up with the constant pitch of fuselage. The scheme of the jump maneuver is shown in Fig. 2. During a simulation the distance required for the maneuver is defined including the condition of flight over an obstacle within the allowed strip of height .

The method of execution of the maneuver is determined in an iteration process. After the first phase with a lack the pilot's reaction, the rotor blade collective pitch is pulled-up. The flight parameters for the time steps of simulated pull-up are saved in an auxiliary array. At the first attempt of a climb, in the following time steps of a helicopter motion, the collective pitch is being increased till one of the assumed limitations is achieved. Then, the boundary collective pitch is kept till the prognosis of the height supposed to be reached at the next step of solution h_{prog1} will exceed the height of an obstacle:

$$h_{prog1} = z + w * dt + a_z * \frac{dt^2}{2} > h_{obstacle} \quad , \tag{6}$$

where
z – temporary height of helicopter,
w –vertical speed of helicopter,
a_z – helicopter vertical acceleration,
dt – time step of solution.

At the next time step, with fulfilled prognosis of a flight above an obstacle, the collective pitch is reduced. For the following steps, despite the collective pitch decrease, the helicopter continues to climb. The simulation of a maneuver in the phase of the collective pitch reduction is interrupted if the prognosis of the flight height h_{prog2} exceeds the sum of the obstacle height and the allowed strip height:

$$h_{prog2} > h_{obstacle} + h_{allowed\_strip} \quad . \tag{7}$$

The plot of the height changes for the first attempt of the simulated jump maneuver for data of a light helicopter of mass of 1,100kg is shown in Fig. 4. In this case (Table 1), the high value of collective pitch $\vartheta_o \approx 22.9^0$ is kept up to the 63rd step of simulation, when the helicopter achieved the height z=39.84m. For the following three steps of the solution, despite the reduction of the collective pitch to $\vartheta_o = 19.63^0$, the helicopter reached the height z=44.65m with simultaneous little decrease of the climb speed from w=8.28m/s to w=7.50m/s. The prognosis of the flight height for the next time step exceeded the assumed strip of the allowed height. In that situation, after an interruption of the first attempt, the cycle of jump solution was repeated, but then the phase of maintaining the high collective pitch level was shortened by one time step, which meant an earlier beginning of a collective pitch reduction phase. After four steps with the collective pitch reduced to $\vartheta_o = 17.77^0$ (Table 2) the helicopter reached the height z=44.36m climbing at a lower speed w=6.67m/s and exceeding the height of the allowed strip. The cycle of shortening the high collective pitch phase and extension the phase of reducing the collective pitch is continued till the flight height of helicopter is kept within the limits of the allowed strip. The distance flown by a helicopter till it stops the ascent flying above an obstacle within the allowed strip is assumed as the distance required for a jump avoidance maneuver. For the example data of a light helicopter with the mass of 1,100kg flying at speed of 80km/h, the distance required to perform the jump avoidance maneuver over the obstacle of height of 40m is equal to x=225m. After the obstacle fly-over at the reduced collective pitch, the available rotor thrust was smaller than the helicopter weight, which caused an increase of the helicopter vertical acceleration. To secure against the excessive increase of descent, the prognosis of the vertical speed for the next steps is assumed as follows:

$$w_{prog4} = w + a_z * dt * n_{steps} < -10 \quad , \tag{8}$$

where
n_{steps} - number of time steps for prognosis of the helicopter vertical speed (here n_{steps}=4).

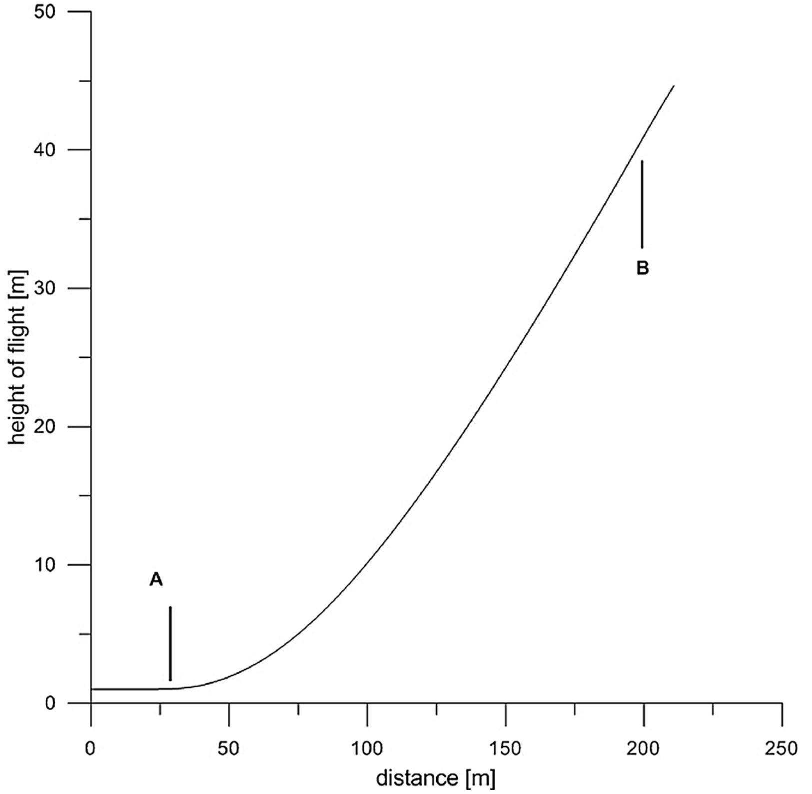

Fig. 4. Height and distance during first attempt of realization climb part of jump obstacle avoidance maneuver; helicopter mass 1,100kg, obstacle height 40m, initial flight height over terrain 1m;
A - beginning of increase of collective pitch,
B - drop down of collective pitch. [Author, 2015]

Table 1. Final part of the first attempt of realization of a jump maneuver over obstacle h_{obst}=40 m, helicopter mass 1,100kg , initial speed 80km/h

Step number	time	x	z	v	w	a_x	a_z	ϑ_o
-	[s]	[m]	[m]	[km/h]	[m/s]	[m/s²]	[m/s²]	[stop.]
58	7.60	173.11	31.78	84.63	7.85	0.19	0.44	22.89
59	7.80	177.81	33.36	84.76	7.94	0.19	0.42	22.89
60	8.00	182.52	34.95	84.90	8.01	0.19	0.39	22.90
61	8.20	187.24	36.56	85.03	8.09	0.19	0.37	22.90
62	8.40	191.97	38.19	85.03	8.19	0.00	0.49	22.88
63	8.60	196.69	39.84	85.03	8.28	0.00	0.46	22.90
collective pitch push-down								
64	8.80	201.42	41.49	85.03	8.20	0.00	-0.38	21.97
65	9.00	206.14	43.10	85.03	7.96	0.00	-1.20	21.00
66	9.20	210.86	44.65	85.03	7.50	0.00	-2.32	19.63

Notations of columns for Table 1 and Table 2:
x – flown distance,
z – height of flight ,
v – flight speed,
w – vertical speed,
a_x, a_z – horizontal and vertical acceleration of helicopter,
ϑ_o – rotor blade collective pitch

Table 2. Final part of second attempt of realization of the jump maneuver over obstacle h_{obst}=40 m helicopter mass 1,100kg , initial speed 80km/h

Step number	time	x	z	v	w	ax	az	tet0
-	[s]	[m]	[m]	[km/h]	[m/s]	[m/s²]	[m/s²]	[stop.]
58	7.60	173.11	31.78	84.63	7.85	0.19	0.44	22.89
59	7.80	177.81	33.36	84.76	7.94	0.19	0.42	22.89
60	8.00	182.52	34.95	84.90	8.01	0.19	0.39	22.90
61	8.20	187.24	36.56	85.03	8.09	0.19	0.37	22.90
62	8.40	191.97	38.19	85.03	8.19	0.00	0.49	22.88
collective pitch push-down								
63	8.60	196.69	39.82	85.03	8.12	0.00	-0.35	21.97
64	8.80	201.42	41.42	85.03	7.88	0.00	-1.18	20.99
65	9.00	206.14	42.95	85.03	7.42	0.00	-2.29	19.63
66	9.20	210.86	44.36	85.03	6.67	0.00	-3.77	17.77

If prognosis of the helicopter vertical speed exceeds the assumed condition (8) limit w_{prog4}=-10m/s, then in the following time steps of simulation the collective pitch is increased until the vertical acceleration of the helicopter reaches zero value a_z=0m/s^2 . The helicopter flight parameters for the first step of a descent phase, when the collective pitch is increased to stop an accelerated descent, are saved in an auxiliary array. A descent flight with a steady vertical speed and a constant collective pitch is continued till a prognosis of the temporary height of the helicopter flight is lower than an assumed height for a phase of flight after passing an obstacle:

$$h_{after\_obstacle} > h_{prog4\_after} = z + w*\left(n_{step\_aft}*dt\right) + \frac{a_z}{2}*\left(n_{step\_aft}*dt\right)^2 \quad , \qquad (9)$$

where n_{step_aft} - number of time steps for prognosis of the helicopter height (here n_{step_aft}=4).

For the fulfilled condition (9), in the following steps of simulation, the collective pitch is increased again up to stop the vertical speed w=0. If a level flight is achieved at a height lower than the demanded height in an area behind an obstacle:

$$h_{flight} < h_{demanded\_behind} \quad , \qquad (10)$$

the cycle of calculation is repeated starting with a phase of the vertical acceleration reduction, which starts one step earlier in comparison to previous cycle. The sequence of calculation with an earlier and earlier increase of the collective pitch is continued till a slowdown of a descent speed is maintained at a greater height than an assumed height of a flight behind an obstacle

$$h_{flight} > h_{demanded\_behind} \quad . \qquad (11)$$

In Fig. 5÷Fig. 8 is shown a run of the iteration process of a jump maneuver over an obstacle. The attempts of climb and next slowdown of the vertical speed of the helicopter are shown as plots of flight height changes due to the flown distance (Fig.5). A more and more early beginning of the collective pitch reduction in the climb phase and earlier increase the collective pitch in the descent phase behind an obstacle influences the speed and acceleration achieved during the maneuver. The time run of the helicopter acceleration is related to the changes of the collective pitch (Fig. 6).

In Fig. 9÷Fig. 12 is shown an iteration of a jump maneuver of avoidance of a long obstacle without a descent phase. The flight path of the helicopter over an obstacle is assumed to be kept within the height limit of the allowed strip. In comparison with the condition (8) the prognosis for this version of an avoidance maneuver at the phase of reduced collective pitch introduces a lower value of the permissible descent speed:

$$w_{prog4} = w + a_z * dt * n_{steps\_long} < -4 \quad , \tag{12}$$

where

n_{step_long} – number of time steps for prognosis of the helicopter vertical speed for jump over the long obstacle (here n_{step_long}=4).

In the case of a jump over a long obstacle a lower value of the allowed vertical speed, according to the condition (12), enables to keep the height of flight within a tolerance strip. In Fig. 13÷Fig. 16 is presented the influence of helicopter mass, fuselage pitch and initial flight speed on an avoidance maneuver of jump over a long obstacle. The calculation results of the required distance to perform the jump avoidance maneuver over a long obstacle due to the different helicopter mass, speed and fuselage pitch are collected in Table 3.

It can be noticed that an increase of the helicopter mass and increase of the helicopter speed extend the required distance of a maneuver. A reduction of the required distance can be achieved at the pulled-up fuselage pitch, which is connected with the backward tilted component of the rotor thrust decelerating the horizontal motion of the helicopter during the climb phase of the maneuver.

Table 3. Influence of fuselage pitch, speed and mass of helicopter on distance of jump maneuver

Influence of fuselage pitch at speed v=80 km/h		
mass [kg]	Fuselage pitch [deg]	distance [m]
1,100	-1.0	225.17
1,100	1.5	199.53
1,100	4.0	177.21
Influnce of flight speed		
mass [kg]	speed [km/h]	distance [m]
1,100	60	167.49
1,100	80	225.17
1,100	100	332.43
Influence of helicopter mass		
mass [kg]	speed [km/h]	distance [m]
1,000	60	143.34
1,100	60	167.49
1,200	60	209.31

Remark: pitch (+) for fuselage pulled-up.

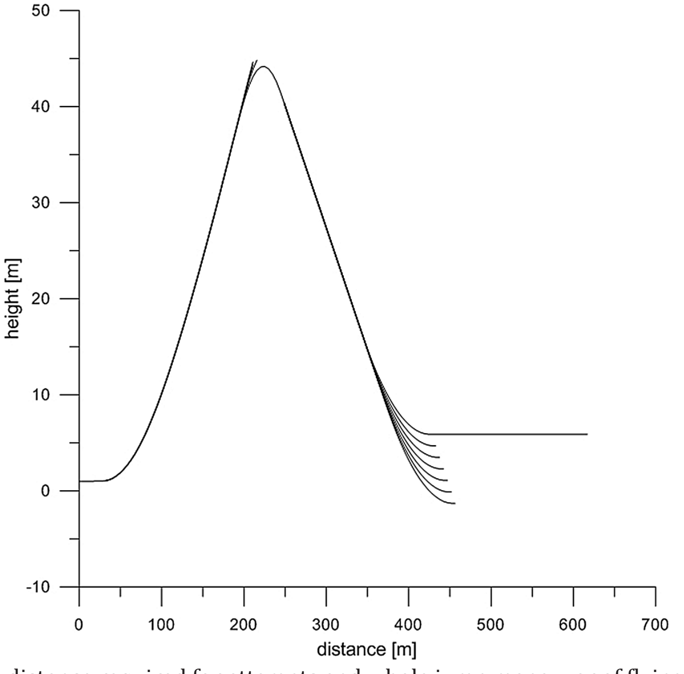

Fig. 5. Height and distance required for attempts and whole jump maneuver of flying over obstacle; helicopter mass 1,100kg, obstacle height 40m,initial flight height over terrain 1m, the end of maneuver at height h> 5m [Author, 2015]

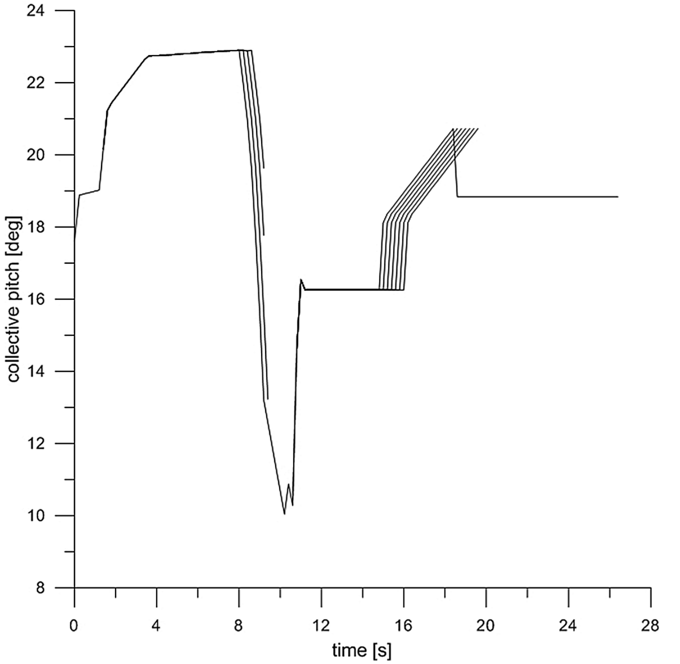

Fig. 6. Changes of rotor collective pitch during jump obstacle avoidance maneuver. Subsequent attempts of maneuver execution with earlier decrease of collective pitch before obstacle and earlier increase of collective pitch at recovery phase after obstacle. Helicopter mass 1,100kg, obstacle height 40m, initial flight height over terrain 1m, finish of maneuver at height h>5 m. [Author, 2015]

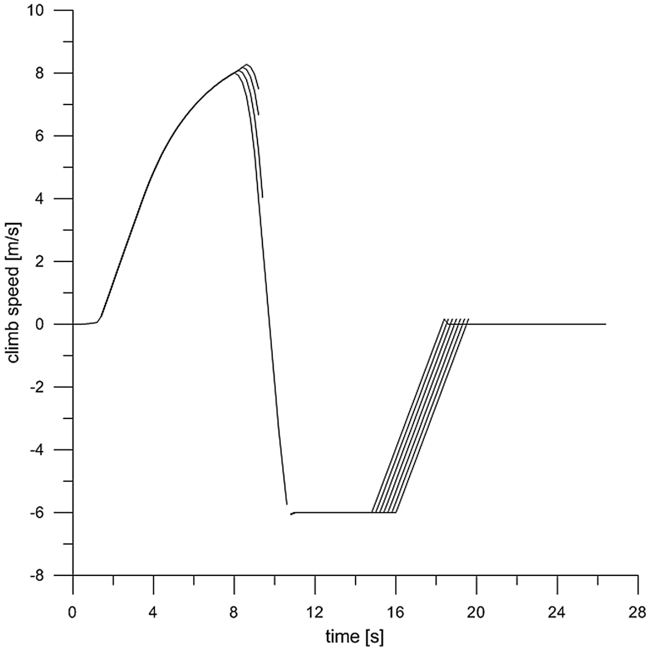

Fig. 7. Changes of climb speed during jump obstacle avoidance maneuver. Subsequent attempts of maneuver execution with earlier decrease of collective pitch before obstacle and earlier increase of collective pitch at recovery phase after obstacle. Helicopter mass 1,100kg, obstacle height 40m, initial flight height over the terrain 1m, end of the maneuver at height h>5 m. [Author, 2015

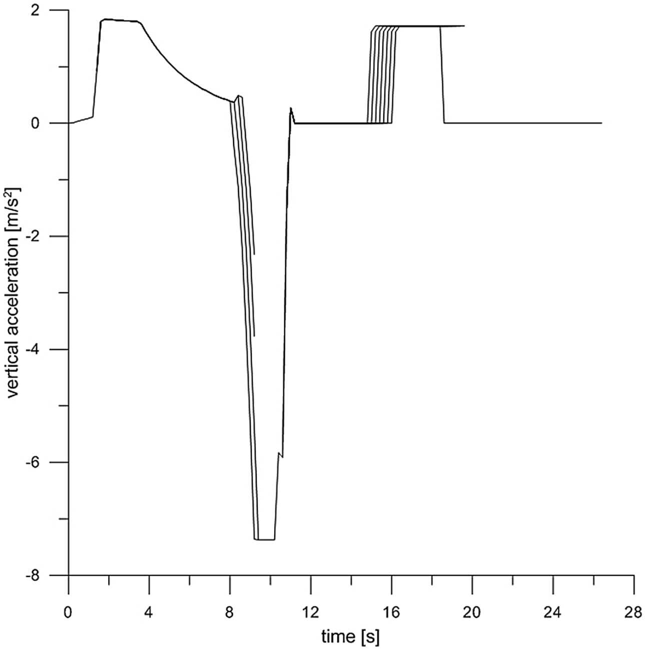

Fig. 8. Changes of helicopter vertical acceleration during jump obstacle avoidance maneuver. Subsequent attempts of maneuver execution with earlier decrease of collective pitch before obstacle and earlier increase of collective pitch at recovery phase after obstacle. Helicopter mass 1,100kg, obstacle height 40m,initial flight height over terrain 1m, end of maneuver at height h>5 m. [Author, 2015]

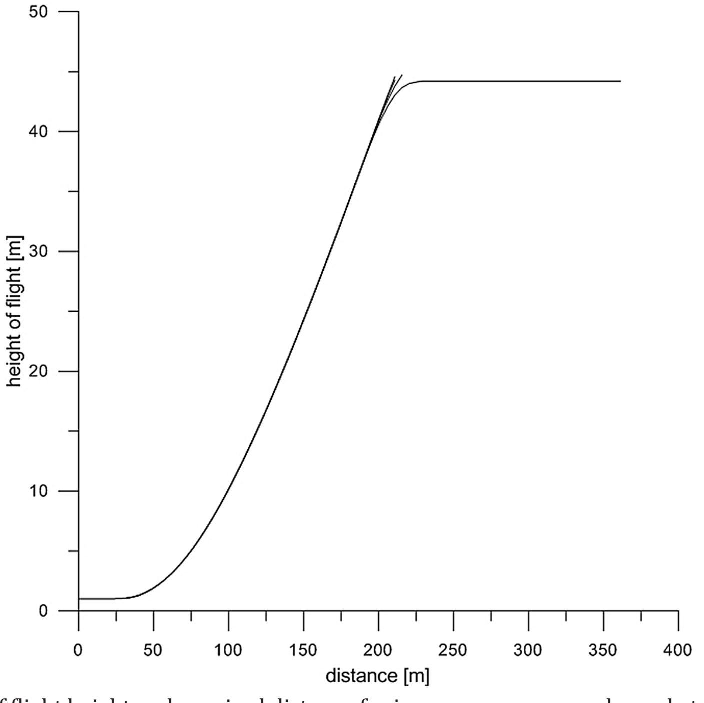

Fig. 9. Changes of flight height and required distance for jump maneuver over long obstacle of 40m height. Flight path passes within permissible strip of 5m over obstacle height; helicopter mass 1,100kg. [Author, 2015]

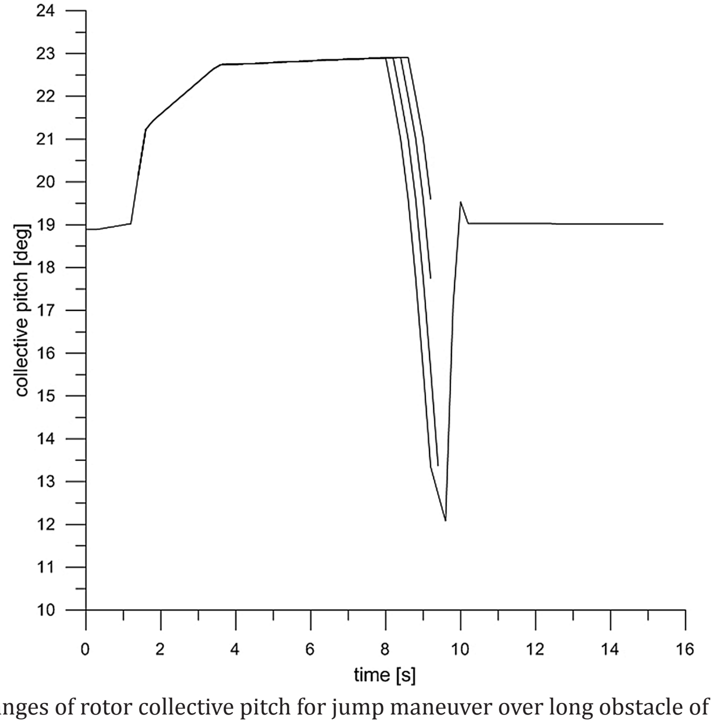

Fig. 10. Changes of rotor collective pitch for jump maneuver over long obstacle of 40 m height. Permissible strip of 5m over obstacle height. Helicopter mass 1,100kg. [Author, 2015]

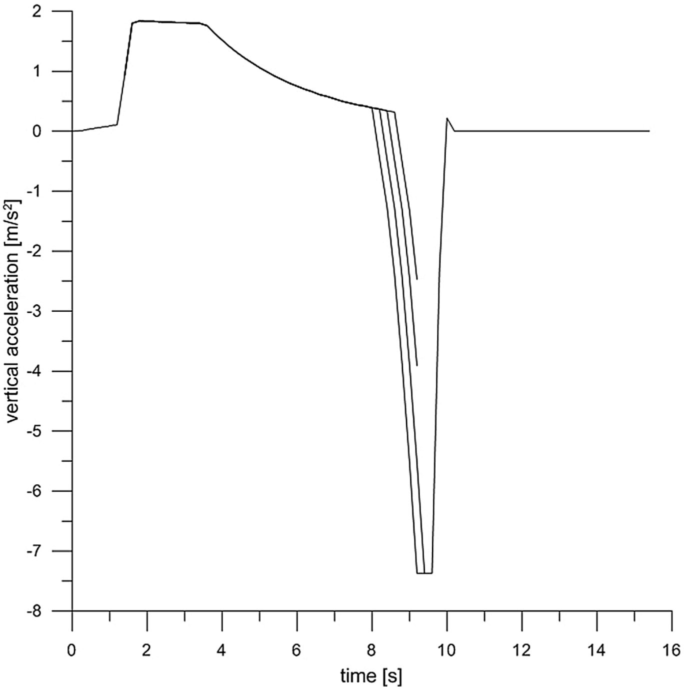

Fig. 11. Changes of helicopter vertical acceleration for jump maneuver over long obstacle of 40m height. Permissible strip of 5m over obstacle height. Helicopter mass 1,100kg, [Author, 2015]

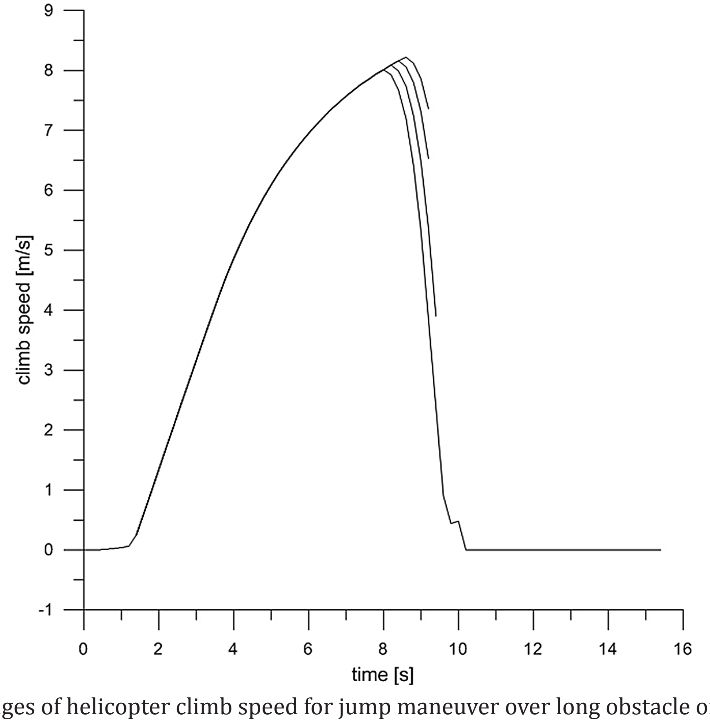

Fig. 12. Changes of helicopter climb speed for jump maneuver over long obstacle of 40m height. Permissible strip of 5m over obstacle height. Helicopter mass 1,100kg. [Author, 2015]

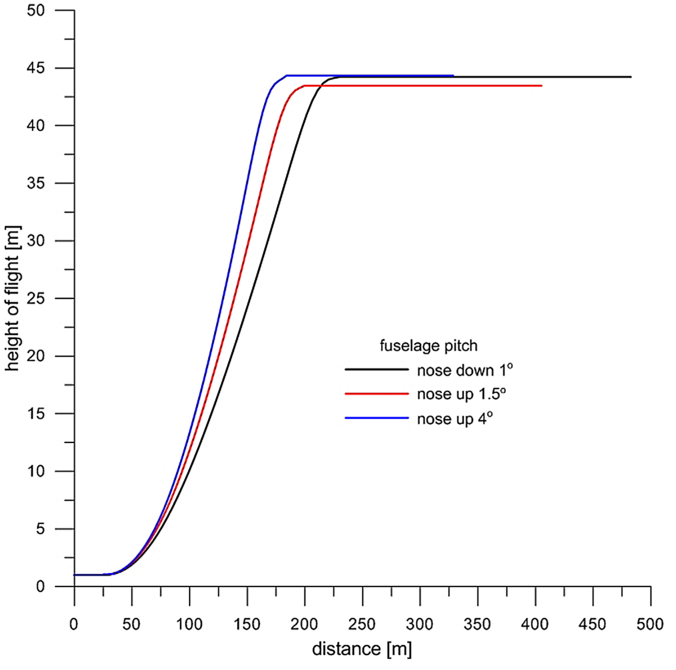

Fig. 13. Changes of flight height and required distance for t jump maneuver over long obstacle of 40m height. Maneuver performed at different fuselage pitch and finished within permissible strip of 5m over obstacle height. Initial flight speed 80km/h; helicopter mass 1,100kg. [Author, 2015]

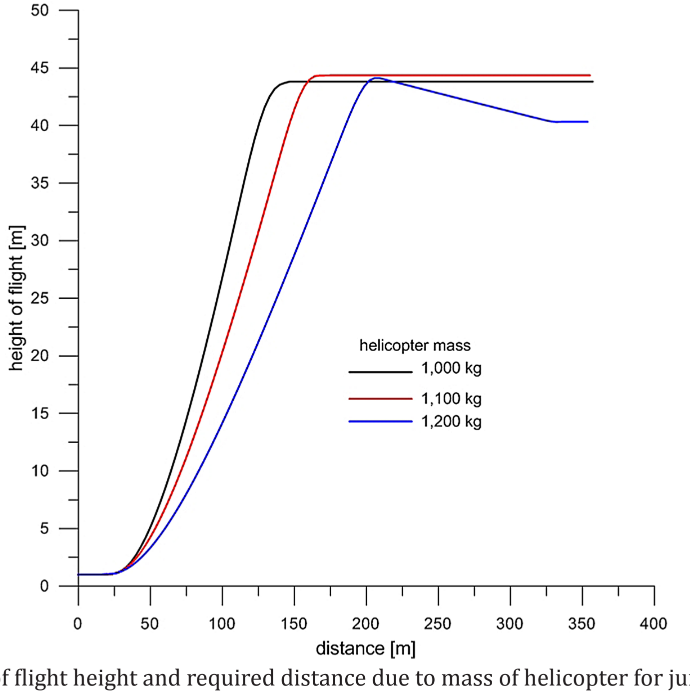

Fig. 14. Changes of flight height and required distance due to mass of helicopter for jump maneuver over long obstacle of 40m height. Maneuver finished within permissible strip of 5m over obstacle height. Initial flight speed 60km. [Author, 2015]

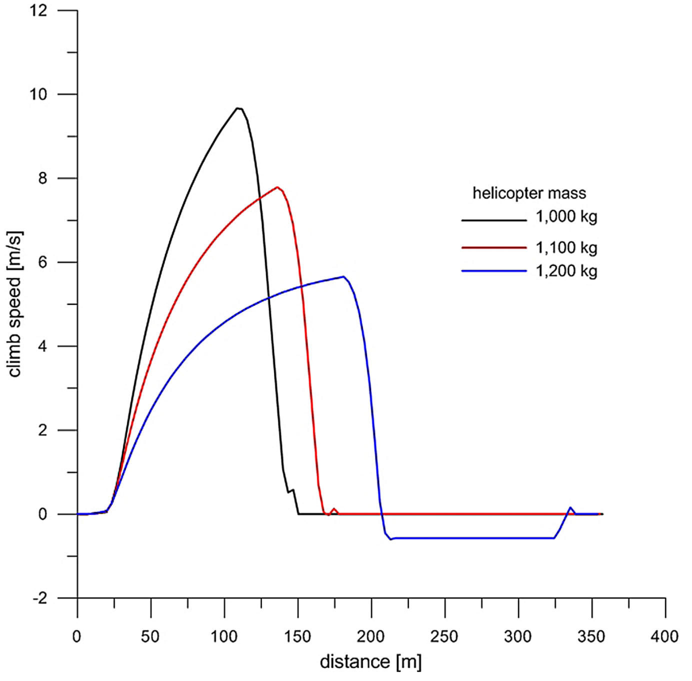

Fig. 15. Changes of climb speed due to mass of helicopter for jump maneuver over long obstacle of 40m height. Maneuver finished within permissible strip of 5m over obstacle height. Initial flight speed 60km/h. [Author, 2015]

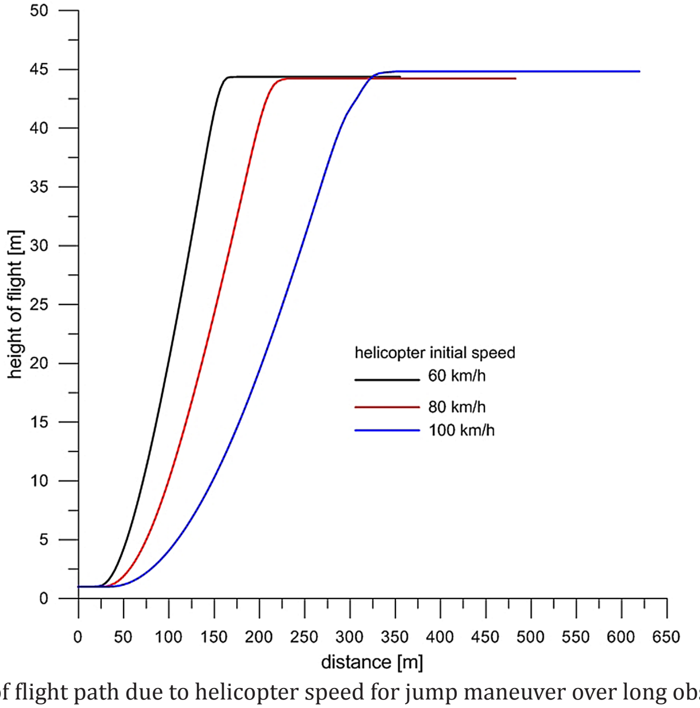

Fig. 16. Changes of flight path due to helicopter speed for jump maneuver over long obstacle of 40m height. Maneuver finished within permissible strip of 5m over obstacle height. Helicopter mass 1,100 kg. [Author, 2015]

4. HORIZONTAL S-TURN MANEUVER

A horizontal S-turn maneuver is assumed as two following turns in the opposite sides. The radius of the turn is connected with a possibility to generate a magnitude of the centripetal force, which depends on a helicopter roll angle and an available main rotor thrust. At a steady turn, the vertical component of the rotor thrust counterbalances the weight of a helicopter

$$m * g = T * cos(\varphi_{roll}) \quad , \tag{13}$$

where

φ_{roll} - roll angle of helicopter (rotor shaft axis),

m - mass of helicopter,

g - acceleration of gravity.

The centripetal acceleration due to roll of the helicopter can be determined as follows:

$$a_{y\_cent} = g * tg(\varphi_{roll}) \quad , \tag{14}$$

The roll angle possible to achieve in steady turn φ_{roll_limit} is limited as a result of reaching the maximum power of engine or generating the critical rotor thrust due to an appearance o of a separation flow zone. For the maneuver of a simulated turn, it is assumed that during the time step of a simulation the helicopter performs a turn at a temporary constant radius of a flight path and a constant helicopter roll. In the following time steps the curvature of the flight path is being changed according to a permitted roll rate limitation $(\Delta\varphi_{roll}/\Delta t)_{\max}$, which is assumed as input data of the simulation program. Taking into account the maximum roll rate $(\Delta\varphi_{roll}/\Delta t)_{\max}$, the roll angle of a helicopter is kept during a turn beneath the roll limit due to available engine power and rotor thrust

$$\varphi_{roll} \leq \varphi_{roll\_\lim it} \quad . \tag{15}$$

Assuming that the helicopter flight path consists of arc segments, the following parameters can be defined:

- radius of the turn at time step Δt

$$r_{\Delta t\_turn} = \frac{v * v}{a_{y\_cent}} \quad , \tag{16}$$

where v - flight speed

- angular velocity for motion along the arc of radius $r_{\Delta t\_turn}$

$$\omega_{\Delta t\_turn} = \frac{v}{r_{\Delta t\_turn}} \quad , \tag{17}$$

- change of the yaw angle at time step Δt

$$\Delta\Psi_{\Delta t} = \omega_{\Delta t\_turn} * \Delta t \quad , \tag{18}$$

- yaw angle at the next time step

$$\Psi_{i+1} = \Psi_i + \Delta\Psi_{\Delta t} \quad . \tag{19}$$

To determine the first part of S-turn maneuver (Fig. 3) for the following attempts of the turn realization, the calculation cycle includes an increased by one the number of growing roll and yaw steps and then, the same number of steps with diminishing roll but still a growing yaw.

Table 4. Fragment of iteration of S-turn avoidance maneuver for helicopter of mass 1,100kg at speed 80km/h.

time	x	y	a_{y_cent}	φ_{roll}	Ψ	ϑ_X	ϑ_o
[s]	[m]	[m]	[m/s²]	[deg]	[deg]	[deg]	[deg]
The last attempt of roll increment and decrement during first turn of maneuver							
1.40	31.11	0.01	0.51	3.00	0.27	1.288	17.61
1.80	40,00	0.14	1.54	8.94	1.59	1.309	17.72
2.20	48.88	0.57	2.57	14.68	3.98	1.351	17.94
2.60	57.72	1.44	3.60	20.15	7.42	1.411	18.26
3.00	66.48	2.92	4.63	25.25	11.93	1.488	18.66
3.40	75.08	5.17	5.66	29.96	17.5	1.578	19.15
3.80	83.43	8.22	4.63	25.25	22.53	1.488	18.66
4.20	91.51	11.92	3.60	20.15	26.51	1.411	18.26
4.60	99.35	16.09	2.57	14.68	29.43	1.351	17.94
5.00	107.02	20.60	1.54	8.94	31.28	1.309	17.72
5.40	114.58	25.27	0.51	3.00	32.08	1.288	17.61

Remark: notations of columns of the Table 4:
x – flown distance in direction of the obstacle,
y – side position of the helicopter measured along width of the obstacle,
a_{y_cent} – centripetal acceleration of helicopter ,
φ_{roll} - helicopter roll
Ψ – helicopter yaw
ϑ_X - lateral deflection of the swashplate
ϑ_o - rotor collective pitch

The example of the helicopter roll and yaw changes during the cycle of calculations are collected in Table 4. Increasing the numbers of steps for growth and a reduction of the angle of helicopter roll is conducted till the lateral displacement *y* achieved by a helicopter is bigger than the half of obstacle dimension

$$y > 0{,}5 * y_{obst} \quad , \tag{20}$$

If the limit of the helicopter roll is reached prior to fulfillment of the condition (20), then the next calculation cycles include an increasing number of steps with a roll angle limited to a permissible value. The second part of an S-turn maneuver (Fig. 3) is performed in the opposite side as a mirror copy of the first part turn. A simulation program concerning an S-turn maneuver applies the same method of calculation of acceptable acceleration increments in time step as method used in the case of a jump maneuver. The acceleration increments for the assumed limitations of power, rotor thrust and swashplate deflection are calculated in each time step of the simulation. The least value of the acceleration increment determines an acceptable change of the centripetal acceleration of a helicopter

The results of simulating the S-turn avoidance maneuver for the obstacle 50m wide are presented in Fig. 17÷Fig. 24. For the considered helicopter mass of 1,100kg flying the speed of 80km/h in the S-turn maneuver the roll angle is limited to φ_{roll}=32.90^0 (Fig. 17). The run of changes of the helicopter lateral displacement during the iteration is shown in Fig. 18 and the distance required for the S-turn avoidance maneuver presents Fig. 19. The changes of the collective pitch during iteration of the first part of maneuver and the continuation plot of the collective pitch control for the second part of the maneuver are shown in Fig. 20. The plots of parameters of a helicopter motion: lateral velocity measured along width of the obstacle, roll angle and yaw angle can be seen in Fig. 21, Fig. 22 and Fig. 23, respectively. The results of calculations concerning the influence of flight speed on the distance required to perform the S-turn avoidance maneuver are collected in Table 5. For the example data: the helicopter mass of 1,100kg, flight speed of 80km/h and the obstacle dimension of 50m, the helicopter roll angle achieved in turn is smaller than the value of a roll angle limit related to the magnitude of the available rotor thrust. In the case of flights at higher speeds, a lower permissible limits of a roll angle influence a decrease of the flight path curvature, which increases the required distance of an S-turn horizontal avoidance maneuver. Plots of the flight paths of the S-turn maneuvers inserted in Fig. 24 show a growth of the required distance for an obstacle avoidance due to the helicopter speed increase.

Table 5. Influence of flight speed on distance required for S-turn avoidance maneuver

Helicopter mass	Flight speed	Roll limit	Roll achieved in maneuver	Distance of maneuver	Sort of limit
[kg]	[km/h]	[deg]	[deg]	[m]	
1,100	80	32.90	29.69	210.69	rotor thrust
1,100	100	26.58	26.58	268.87	rotor thrust
1,100	120	19.92	19.92	365.93	rotor thrust

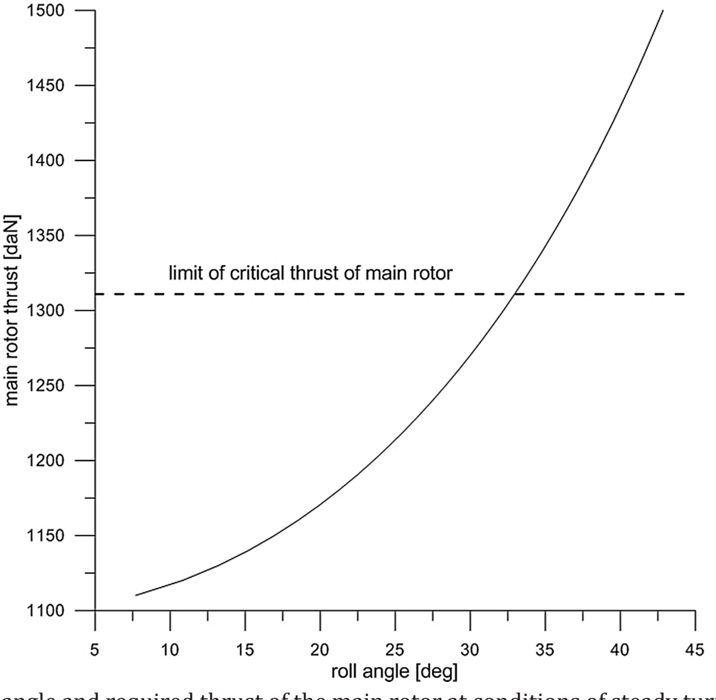

Fig. 17. Roll angle and required thrust of the main rotor at conditions of steady turn at speed of 80 km/h for helicopter of 1,100kg mass. [Author, 2015]

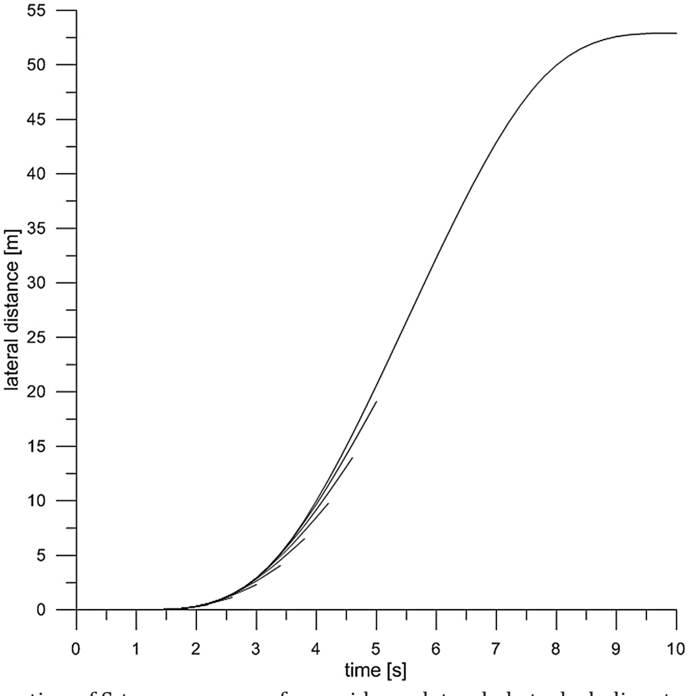

Fig. 18. Run of iteration of S-turn maneuver for avoidance lateral obstacle, helicopter flight at speed of 80 km/h, dimension of obstacle y_{obst}=50m, helicopter mass 1,100kg. [Author, 2015]

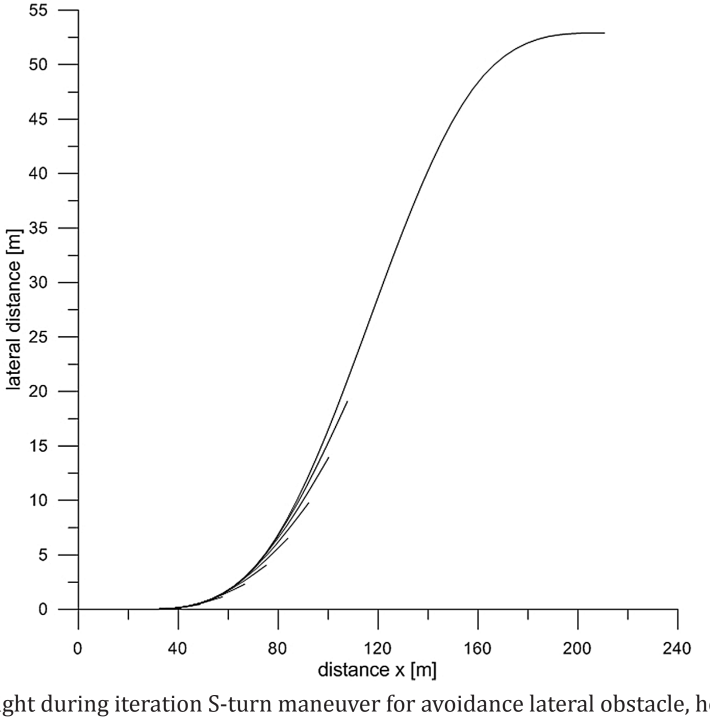

Fig. 19. Path of flight during iteration S-turn maneuver for avoidance lateral obstacle, helicopter flight at speed of 80 km/h, dimension of obstacle y_{obst}=50 m, helicopter mass 1,100kg. [Author, 2015]

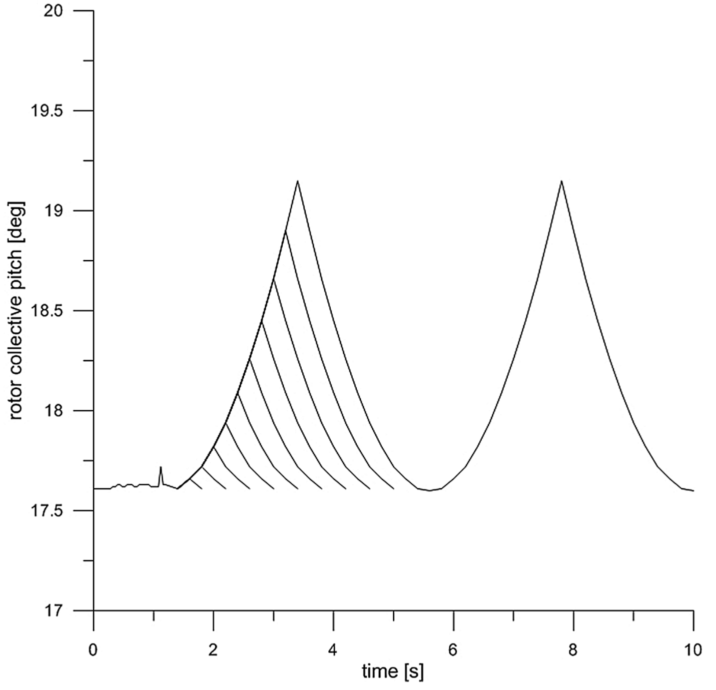

Fig. 20. Change of rotor collective pitch during iteration S-turn maneuver for avoidance of a lateral obstacle, flight at speed of 80 km/h, dimension of obstacle y_{obst}=50 m, helicopter mass 1,100kg. [Author, 2015].

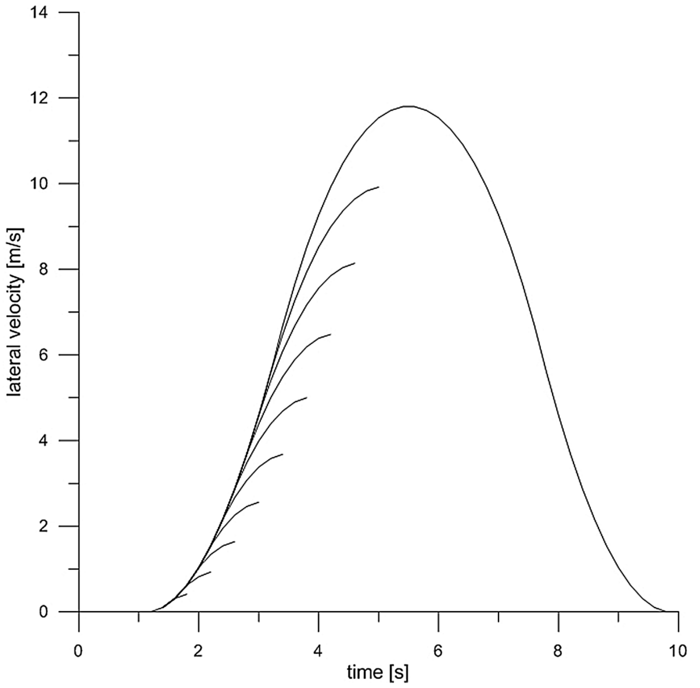

Fig. 21. Change of lateral velocity during iteration t S-turn maneuver for avoidance of a lateral obstacle, flight at speed of 80 km/h, dimension of obstacle y_{obst}=50 m, helicopter mass 1,100kg. [Author, 2015].

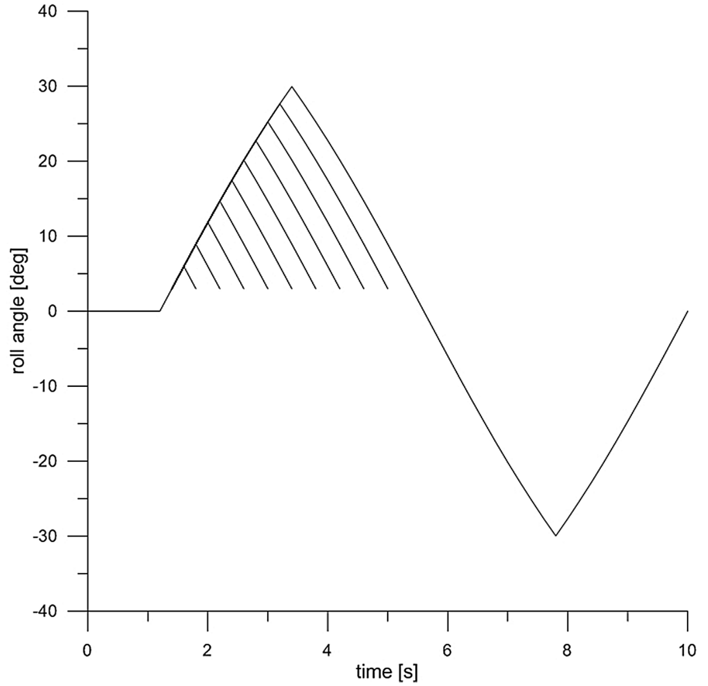

Fig. 22. Change of roll angle during iteration S-turn maneuver for avoidance of a lateral obstacle, flight at speed of 80 km/h, dimension of obstacle y_{obst}=50 m, helicopter mass 1,100kg. [Author, 2015].

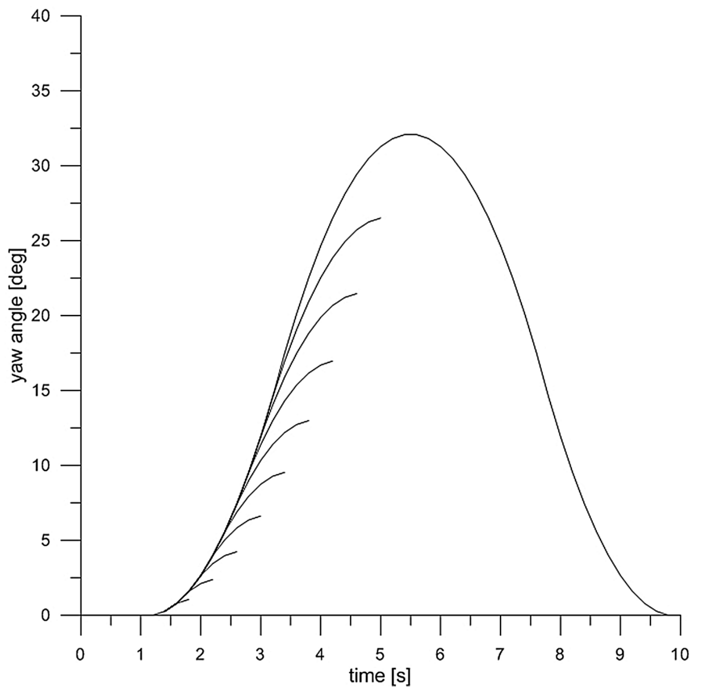

Fig. 23. Change of yaw angle during iteration S-turn maneuver for avoidance of a lateral obstacle, flight at speed of 80 km/h, dimension of obstacle y_{obst}=50 m, helicopter mass 1,100kg. [Author, 2015]

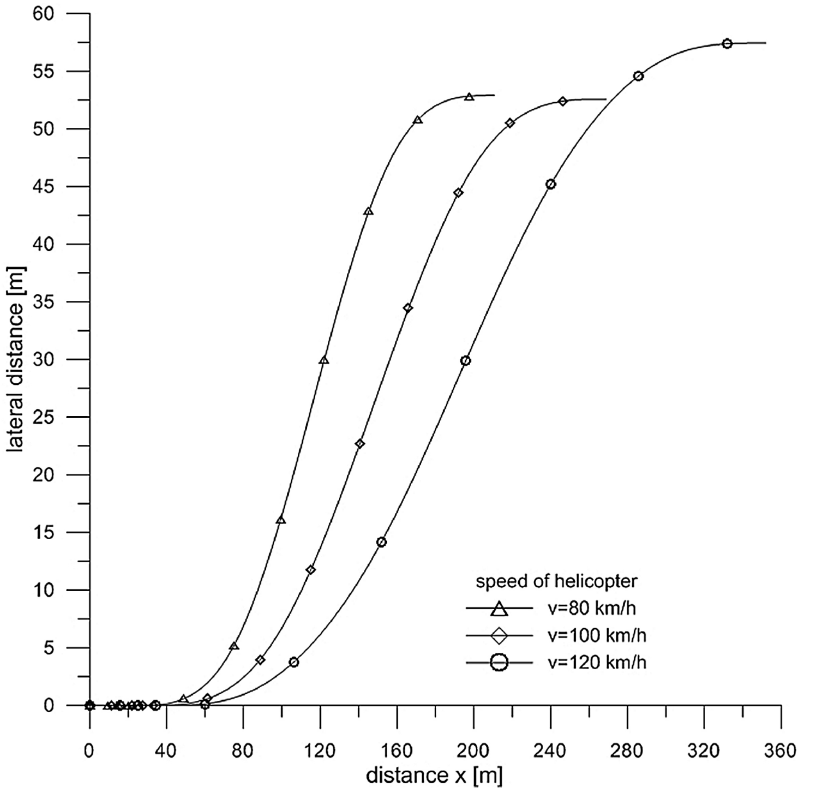

Fig. 24. Path of flight for S-turn maneuvers due to speed of helicopter, dimension of obstacle y_{obst}=50 m; helicopter mass 1,100kg. [Author, 2015]

5. CONCLUSIONS

The simulation program enables to calculate the required distance for performing an obstacle avoidance maneuver without exceeding the helicopter operational limitations.

The simplified model of the point-mass helicopter makes it possible to obtain a short time of execution of a simulation program. For example data the simulation calculation concerning a single avoidance maneuver takes approximately 1 second. The relatively short time of a computer simulation, in comparison with 10 second duration a real maneuver, makes it possible to apply a simulation program as a part of the system providing a pilot with information on the distance of the maneuver and the required control functions in a few second time before the real situation occurs.

In the present form, the simulation program may be useful to determine an acceptable way of an avoidance maneuver execution, which includes helicopter operational limits such as the maximum power of the engine, an available rotor thrust, a control margin and a permissible rate of control change. Additional conditions and limitations related to the helicopter motion are applied: limits of the helicopter pitch and roll angles, tolerance strip for the flight path, time delay of a pilot's reaction.

Division of the simulated avoidance maneuvers into basic components makes it easier to prepare a modified version of a program to simulate other helicopter maneuvers.

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SYMULACJA GRANICZNYCH MANEWRÓW ŚMIGŁOWCA OMIJANIA PRZESZKODY Z PRZEWIDYWANĄ FUNKCJĄ STEROWANIA

Streszczenie

Przedstawiono uproszczoną metodę symulacji sterowanego lotu śmigłowca, którą zastosowano w programie określającym sposób wykonania dwóch wersji manewru omijania przeszkody, pionowego przeskoku oraz poziomego manewru. Uwzględniając eksploatacyjne ograniczenia śmigłowca w procesie iteracyjnym jest wyznaczana funkcja sterowania śmigłowca wymagana do wykonania manewru. Wyznaczenie symulowanego manewru jest prowadzone przy warunku przejścia toru lotu w granicach przyjętego pasma tolerancji.

Słowa kluczowe: śmigłowiec, manewry, symulacja.