NUMERICAL PREDICTION OF BEHAVIOUR OF A HELICOPTER PERFORMING THE NAP-OF-THE-EARTH MANOEUVRES AND ITS EXPERIMENTAL VERIFICATION

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Abstract

The paper presents selected results of numerical prediction of behaviour of a helicopter performing the nap-of-the-earth manoeuvres. The numerical analysis was verified experimentally. On the basis of these investigations a guideline was worked out. They allowed to optimise these manoeuvres.

1. Introduction

Knowledge of flight characteristics of a helicopter is very important for its users. It is particularly important in the case of the nap-of-the-earth flights, when the distance between a helicopter and the ground is extremely small. The ADS norm /*Aeronautical Design Standard – Handling Qualities Requirements for Military Rotorcraft*/ is the main source of objective criteria for estimation of flight characteristics of a helicopter.

On the basis of this norm a great deal of experimental investigations were performed for the Polish *Sokol* helicopter. Test flights followed numerical simulations of each manoeuvre. These simulations enabled theoretical prediction of behaviour of the helicopter. Their results were analysed in detail. Next, a scenario of a test flight was determined and the flight was performed. A lot of flight and control parameters were recorded. Then, on the basis of these courses the way of the flight execution was discussed. Simultaneously, numerical reconstruction of the flight was done.

2. Mathematical model of a helicopter

A mathematical model of the aircraft with nonlinear inertial cross-coupling can be written in the following form:

$$\frac{d\overline{X}}{dt} = \dot{\overline{X}} = \overline{G}(t, \overline{X}, \overline{S}) \qquad (2.1)$$

where $\overline{X} = (U,V,W,P,Q,R,\Theta,\Phi,\Psi,x_g,y_g,z_g,\omega)^T$ is the vector of the helicopter motion parameters. We have:

- linear velocities U,V,W and angular velocities of the fuselage P,Q,R;
- angles and coordinates describing spatial orientation and position of the fuselage Θ,Φ,Ψ, x_g,y_g,z_g;
- angular velocity of the main rotor ω

$\overline{S} = (\theta_0,\kappa_s,\eta_s,\varphi_{tr})^T$ is the vector of control parameters:

- θ_0 - is the angle of collective pitch of the main rotor;
- κ_s - is the control angle in the longitudinal motion;
- η_s - is the control angle in the lateral motion;
- φ_{tr} - is the angle of collective pitch of the tail rotor.

The set (2.1) comprises the equation of angular motion of the main rotor. Dynamics of this motion, with engines deceleration and acceleration phenomena, is also considered - a model of rotation regulation is included in this equation. This problem has been described in [5].

Motions of blades are considered separately, simultaneously with motions of a fuselage. Average values of forces and moments produced by the main rotor and acting on the fuselage are calculated. Position of the main rotor cone is determined by resolving a set of nonlinear algebraic equations:

$$\overline{\overline{E}}(\overline{X},\overline{S},\overline{\beta})\overline{\beta} = \overline{F}(\overline{X},\overline{S},\overline{\beta}) \qquad (2.2)$$

where $\overline{\beta} = (a_0, a_1, b_1)$ is a vector determining orientation of the cone in relation to the fuselage. The flapping motion is described by a Taylor series:

$$\beta = a_0 - a_1 \cos\psi - b_1 \sin\psi \qquad (2.3)$$

ψ - azimuth of a blade /0^0 at the tail region/.

It should be underlined that all nonlinear inertial cross-couplings are included into equations (2.1) and (2.2). The only simplifications are connected with modelling of blades aerodynamics. They are determined by a certain applied method of calculation of forces produced by blades.

Detailed description of determining of equations (2.1) and (2.2) can be found in [3] and [4].

All simulations are performed making use of inverse dynamics /[5] ÷[11]/. It means that at the beginning constrains describing motion of the helicopter are determined and next, on the basis of these constraints, control inputs are calculated. Many different manoeuvres were analysed in this way. As an example a hurdle-hp manoeuvre is presented below. Influence of changes of constrains on the control signals is discussed.

3. Numerical investigation of the hurdle-hop manoeuvre

The hurdle-hop is a terrain following manoeuvre. It is applied to avoid detection whilst passing obstacles at low level in nap-of-the-earth flights. This manoeuvre should be performed symmetrically with sidestep constrained to be zero.

For the purpose of simulation it was assumed that the manoeuvre was performed on the vertical plane. It meant that yawing and rolling velocities were equal to zero. The two other constraints connected with the longitudinal motion were defined as follows:

the pitching angular velocity:

$$Q = \begin{cases} 0 & \textit{for} \;\; t < t_{m1Q},\; t > t_{m4Q} + T_{d4Q} \\ \frac{Q_A}{16}\left(\cos 3p\frac{t\text{-}t_{m1Q}}{T_{d1Q}} - 9\cos p\frac{t\text{-}t_{m1Q}}{T_{d1Q}} + 8\right) & \textit{for} \;\; t_{m1Q} \le t < t_{m1Q} + T_{d1Q} \\ Q_A & \textit{for} \;\; t_{m1Q} + T_{d1Q} \le t < t_{m2Q} \\ Q_A - \frac{Q_A + Q_B}{16}\left(\cos 3p\frac{t\text{-}t_{m2Q}}{T_{d2Q}} - 9\cos p\frac{t\text{-}t_{m2Q}}{T_{d2Q}} + 8\right) & \textit{for} \;\; t_{m2Q} \le t < t_{m2Q} + T_{d2Q} \\ -Q_B & \textit{for} \;\; t_{m2Q} + T_{d2Q} \le t < t_{m3Q} \\ -Q_B + \frac{Q_B + Q_C}{16}\left(\cos 3p\frac{t\text{-}t_{m3Q}}{T_{d3Q}} - 9\cos p\frac{t\text{-}t_{m3Q}}{T_{d3Q}} + 8\right) & \textit{for} \;\; t_{m3Q} \le t \le t_{m3Q} + T_{d3Q} \\ Q_C & \textit{for} \;\; t_{m3Q} + T_{d3Q} \le t < t_{m4Q} \\ Q_C - \frac{Q_C}{16}\left(\cos 3p\frac{t\text{-}t_{m4Q}}{T_{d4Q}} - 9\cos p\frac{t\text{-}t_{m4Q}}{T_{d4Q}} + 8\right) & \textit{for} \;\; t_{m4Q} \le t \le t_{m4Q} + T_{d4Q} \end{cases}$$

the altitude of flight:

$$H = \begin{cases} 0 & \textit{for} \;\; t < t_{m1H} \\ \frac{H_1}{16}\left(\cos 3p\frac{t\text{-}t_{m1H}}{T_{d1H}} - 9\cos p\frac{t\text{-}t_{m1H}}{T_{d1H}} + 8\right) & \textit{for} \;\; t_{m1H} \le t < t_{m1H} + T_{d1H} \\ H_1 & \textit{for} \;\; t_{m1H} + T_{d1H} \le t < t_{m2H} \\ H_1 + \frac{H_1 - H_2}{16}\left(\cos 3p\frac{t\text{-}t_{m2H}}{T_{d2H}} - 9\cos p\frac{t\text{-}t_{m2H}}{T_{d2H}} + 8\right) & \textit{for} \;\; t_{m2H} \le t < t_{m2H} + T_{d2H} \\ H_2 & \textit{for} \;\; t \ge t_{m2H} + T_{d2H} \end{cases}$$

These formulae were derived on the basis of the time courses recorded during the beginning test flight. Some parameters of these formulas were varied and results of simulation were analysed.

3.1. Altitude effect on hurdle-hop dynamics

Figs. 3.1÷3.14 present results of the hurdle-hop simulation. It is assumed that:

- profile of time histories of the pitching velocity $Q(t)$ and the pitch angle $\Theta(t)$ are the same for all cases /Figs. 3.5, 3.6/;
- the maximum altitude is changed – the following cases are investigated: 1. $H_{\max} = 17m$, 2. $H_{\max} = 10m$, 3. $H_{\max} = 0m$ /Fig.3.1/.

The case 3 is an extreme one - it corresponds to the deceleration-acceleration manoeuvre at a constant altitude. On the basis of the obtained courses the following conclusions can be formulated:

An increase of the hurdle-hop maximum altitude causes a substantial decrease of flight velocity $V_c(t)$ /Fig.3.3/. The higher is the maximum value of altitude, the lower is the final velocity after the manoeuvre.

The overload $N_z(t)$ /Fig.3.4/ increases in the first phase of manoeuvre. Before the maximum altitude is reached it decreases and next again increases, when the helicopter is achieving the top of a trajectory. In the going down phase, $N_z(t)$ decreases at the beginning and finally comes back to the initial value. A range of these variations is different and depends on the maximum value of the altitude. In the case 3, the overload increases strongly and next it decreases quickly and it is at a low level, when the pitch angle is negative. Next the overload increases.

During entering into the manoeuvre a pilot pulls a stick /Fig.3.8/ and simultaneously increases the collective pitch of the main rotor $\theta_0(t)$ /Fig.3.7/. The pitch angle $\Theta(t)$ /Fig.3.6/ starts to grow up. The altitude $H(t)$ /Fig.3.1/ increases too. Before achievement of $H_{\max}$ the pilot decreases the collective pitch and pushes the stick. In the holding phase the stick comes back to the neutral position and the collective pitch increases. In the descent phase the collective pitch is decreased for a moment and next is increased before levelling. At the same time the pilot pulls the stick for the purpose of flight levelling. The extreme values of control inputs depend on an achieved height of the manoeuvre – the higher is $H_{\max}$, the higher they are also.

Fig.3.8 shows that the notch of pulling of the stick depends on the assumed positive pitch angle of the fuselage and doesn't depend on the final altitude of manoeuvre. But the final altitude of flight decides about the range of pulling of the stick in the last phase of hurdle-hop.

Analysis of flapping motion at the azimuth 0^0 /Fig.3.12/ shows that a collision between blade and a tail is possible at the moment, when the helicopter is losing height and the pitch angle is still negative /a nose down/. It corresponds with the final pulling of the stick. Such possibility appears in the case of the hurdle-hop with a high value of $H_{\max}$.

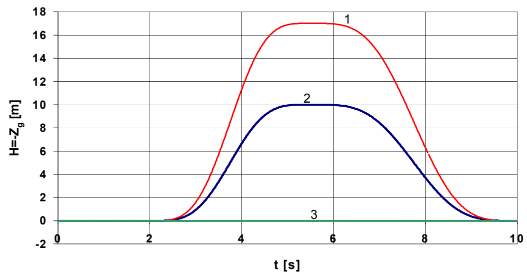

Fig.3.1 Flight altitude $H(t)$

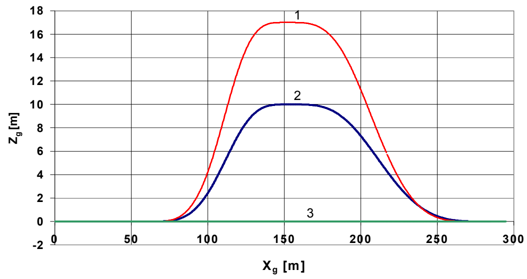

Fig.3.2 Flight trajectory $H(x_g)$

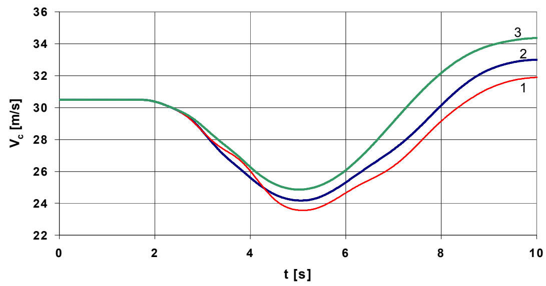

Fig.3.3 Flight velocity $V_c(t)$

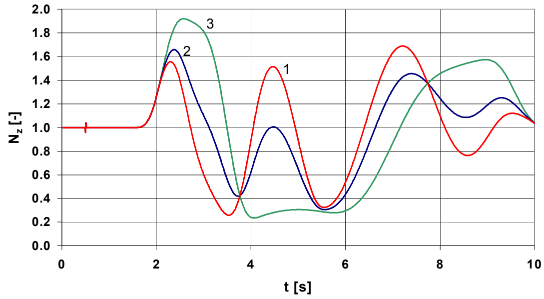

Fig. 3.4 Normal overload $N_z(t)$

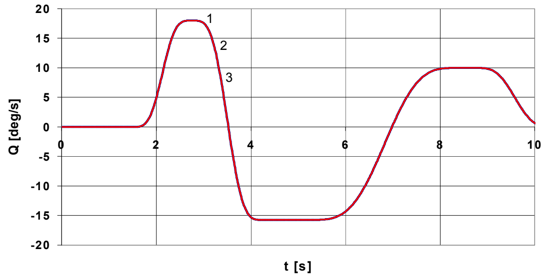

Fig. 3.5 Pitching velocity $Q(t)$

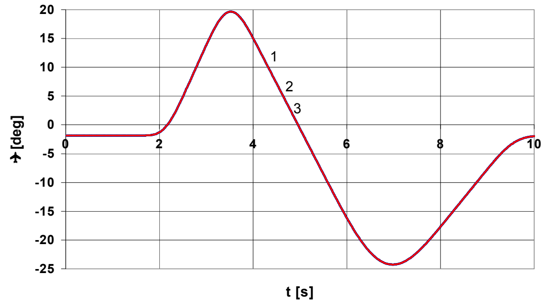

Fig. 3.6 Pitch angle $\Theta(t)$

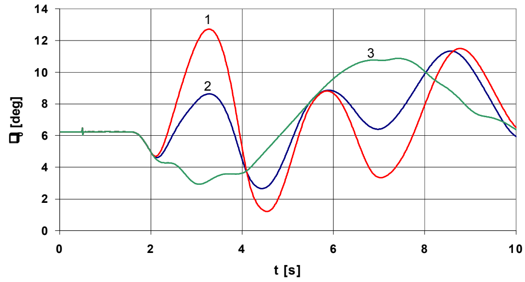

Fig. 3.7 Collective pitch $\theta_0(t)$

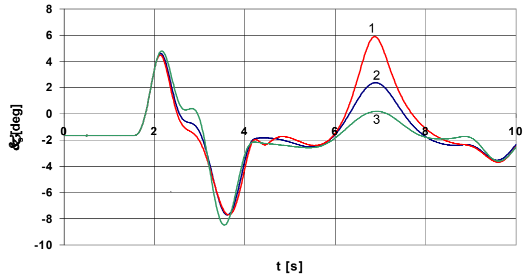

Fig. 3.8 Longitudinal control input $\kappa_S(t)$

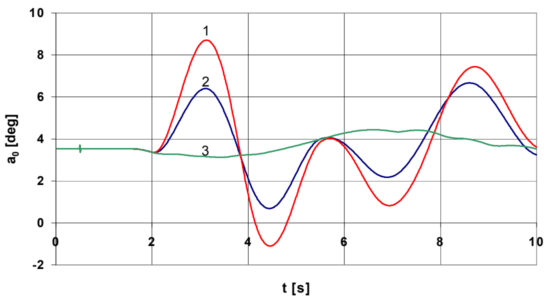

Fig. 3.9 Collective cone angle $a_0(t)$

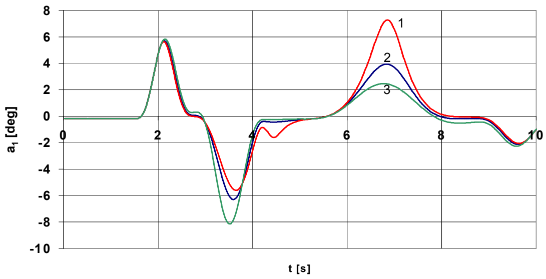

Fig.3.10 Longitudinal cone angle $a_1(t)$

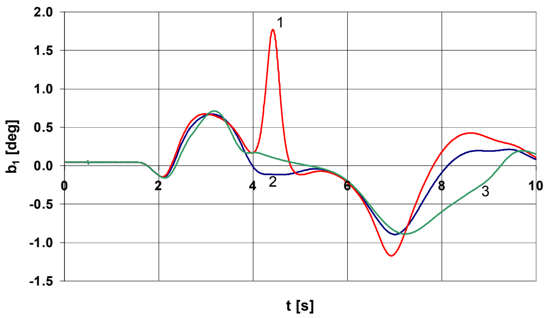

Fig. 3.11 Lateral cone angle $b_1(t)$

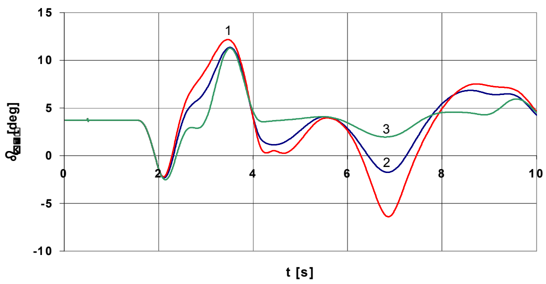

Fig. 3.12 Flapping angle at azimuth 0^0 $\beta_{\psi=0^0}(t)$

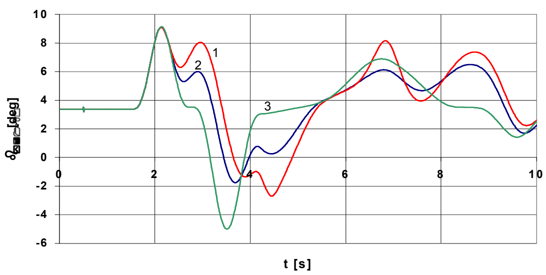

Fig. 3.13 Flapping angle at azimuth 180^0 $\beta_{\psi=180^0}(t)$

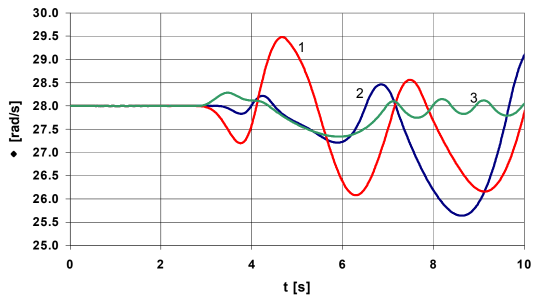

Fig. 3.14 Angular velocity of the main rotor $\omega(t)$

3.2. Pitching rate effect on hurdle-hop dynamics

Figs. 3.15÷3.29 present results of the next hurdle-hop simulation. In this case it is assumed that:

- profile of the time history of the altitude $H(t)$ is the same for all cases /Fig.3.15/ and the maximum value is $H_{\max} = 17m$;
- the extreme values of the pitching velocity $Q(t)$ and the pitch angle $\Theta(t)$ are changed – three cases, denoted as 1, 2 and 3, are investigated /Figs.3.19, 3.20/.

The case 3 is an extreme case and it corresponds to the hurdle-hop manoeuvre with constant pitch angle. On the basis of the obtained courses the following conclusions can be formulated:

Fig. 3.17 shows that the bigger changes of the pitch angle are, the smaller the final velocity is. Simultaneously a trajectory of flight becomes more sharp and the manoeuvre ends closer to the beginning point /Fig.3.16/.

Courses of the normal overload $N_z(t)$ /Fig.3.18/ are similar to described in point 3.1. The range of overload changes is the biggest in the case 3, when the pitch angle is constant.

Figs. 3.21 and 3.22 shows that the greater the range of pitch angle $\Theta(t)$ is, the smaller the necessary changes of the collective pitch $\theta_0(t)$ are. Simultaneously the longitudinal deflections of the stick increases /Fig.3.22/. A probability of a collision between blades and the tail increases too /Fig.3.26/.

As one can observe, the same altitude of hurdle-hop manoeuvre can be obtained for various variations of pitch angle. Small changes correspond to small displacements of the stick and to the increased control of collective pitch. However, the big initial /positive/ pitch angle of the fuselage and subsequent pitching down results in the more vigorous control of the stick and the smaller control of collective pitch. In the first case, the risk of the main rotor angular velocity decrease exists in the climb phase. In the second case, the possibility of collision between blades and the tail appears in the final phase of the hurdle-hop. The safest way of performing of the hurdle-hop is the way in which the collective pitch and the stick is controlled simultaneously.

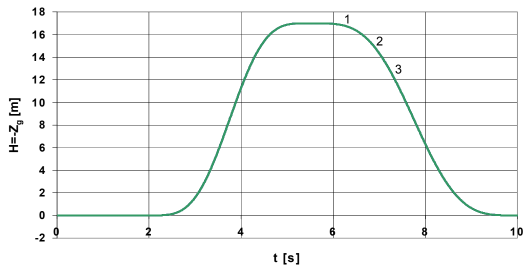

Fig.3.15 Flight altitude $H(t)$

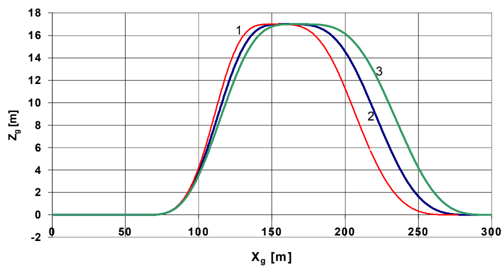

Fig. 3.16 Flight trajectory $H(x_g)$

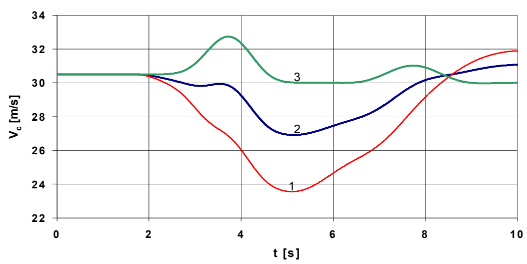

Fig. 3.17 Flight velocity $V_c(t)$

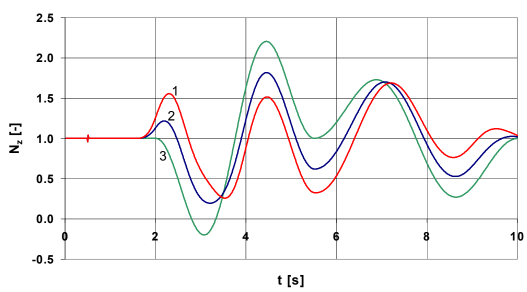

Fig. 3.18 Normal overload $N_z(t)$

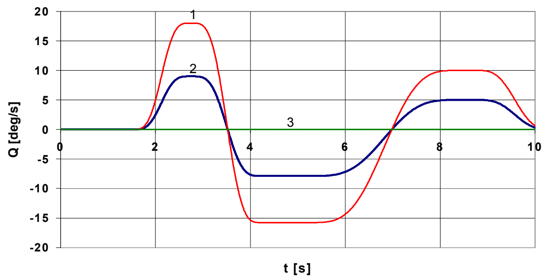

Fig. 3.19 Pitching velocity $Q(t)$

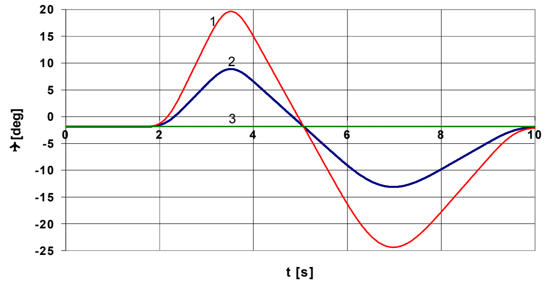

Fig. 3.20 Pitch angle $\Theta(t)$

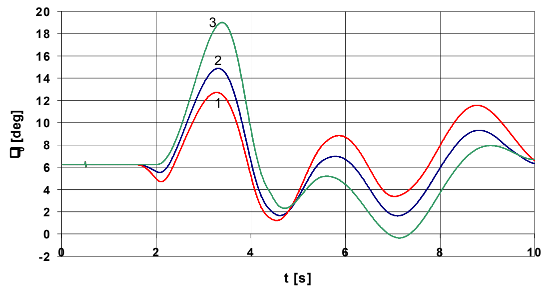

Fig. 3.21 Collective pitch $\theta_0(t)$

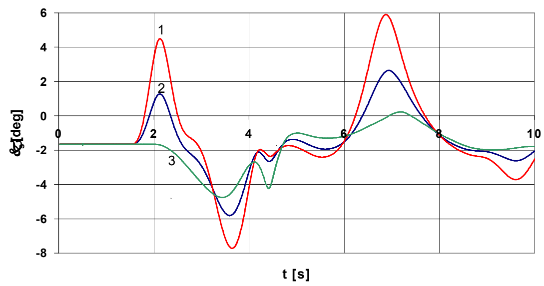

Fig. 3.22 Longitudinal control input $\kappa_S(t)$

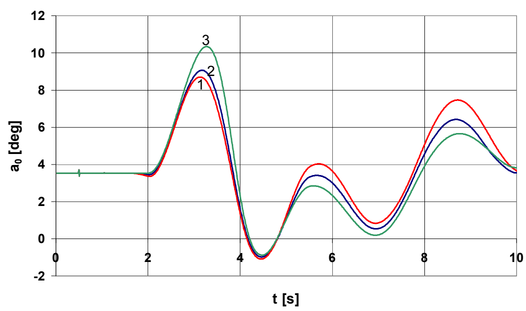

Fig. 3.23 Collective cone angle $a_0(t)$

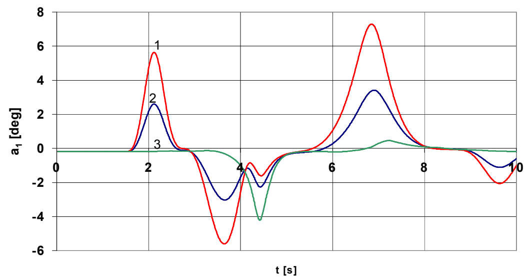

Fig. 3.24 Longitudinal cone angle $a_1(t)$

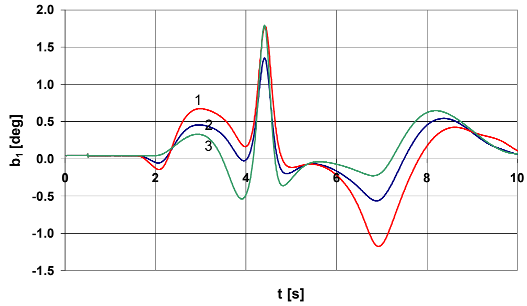

Fig. 3.25 Lateral cone angle $b_1(t)$

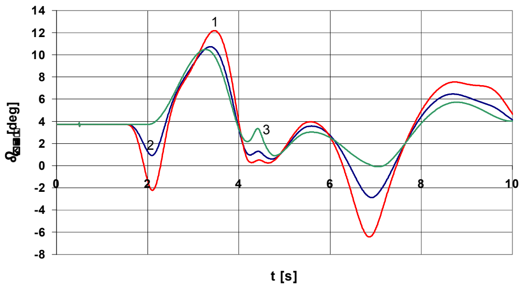

Fig. 3.26 Flapping angle at azimuth 0^0 $\beta_{\psi=0^0}(t)$

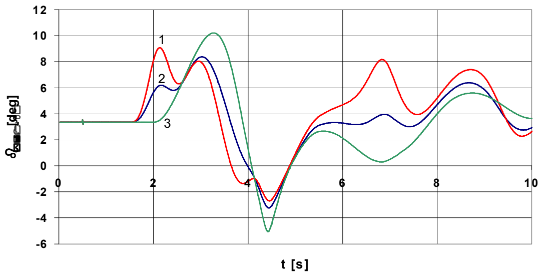

Fig. 3.27 Flapping angle at azimuth 180^0 $\beta_{\psi=180^0}(t)$

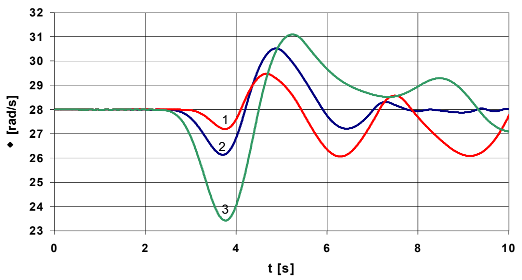

Fig. 3.28 Angular velocity of the main rotor $\omega(t)$

3.3. Beginning time of pitching effect on hurdle-hop dynamics

Figs. 3.29÷3.42 present results of the third stage of hurdle-hop simulation. In this case it is assumed that:

- profile of time history of the altitude $H(t)$ is the same for all cases /Fig.3.15/ and the maximum value is equal to $H_{\max} = 17m$;
- profiles of time histories of the pitching velocity $Q(t)$ and the pitch angle $\Theta(t)$ are the same for all cases /Figs. 3.33, 3.34/;
- the beginning time of pitching /Fig. 3.33/ is varied – three cases, denoted by 1, 2 and 3, are investigated.

The case 1 corresponds to the earliest and the case 3 to the latest start of pitching. The earlier start of pitching up increases intensity of flight velocity braking /Fig.3.31/. The range of normal overload N_z also increases substantially /Fig.3.32/.

Courses presented in Fig.3.40 show that in every case a hazard of collision between blades and the tail exists at azimuth 0^0. It occurs in the second phase of hurdle-hop manoeuvre, when the pitch angle is high in absolute values and negative and the stick is pulled by the pilot in order to pitch the fuselage up. However, Fig.3.41 shows that in the case 3 blades can hit a flapping limiter at azimuth 180^0 in the beginning phase of the manoeuvre before the moment, when the helicopter reaches the maximum altitude. The pitch angle is high and the pilot is pushing the stick.

On the basis of Fig.3.42 one can conclude that the late start of pitching /variant 3/ causes the greater decrease of angular velocity of the main rotor in the final phase of the hurdle-hop manoeuvre.

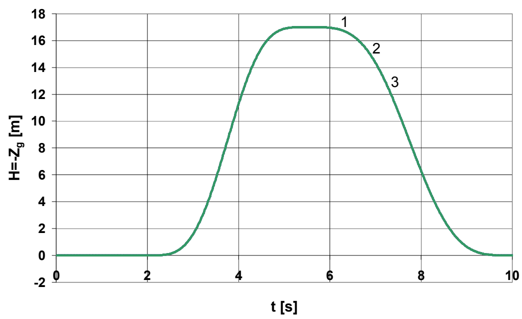

Fig.3.29 Flight altitude $H(t)$

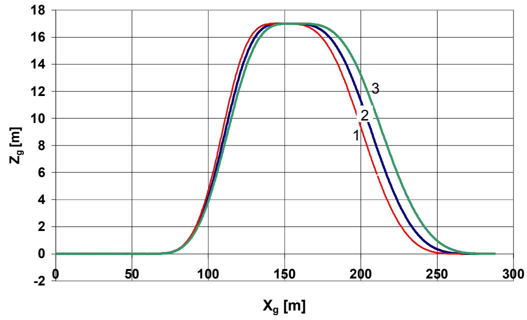

Fig. 3.30 Flight trajectory $H(x_g)$

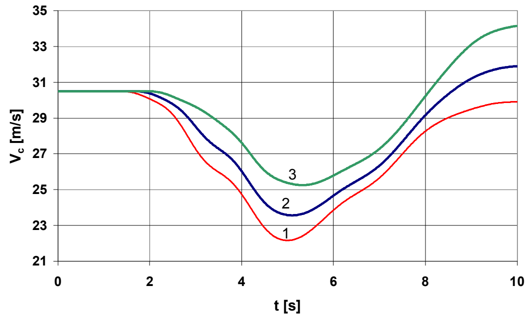

Fig. 3.31 Flight velocity $V_c(t)$

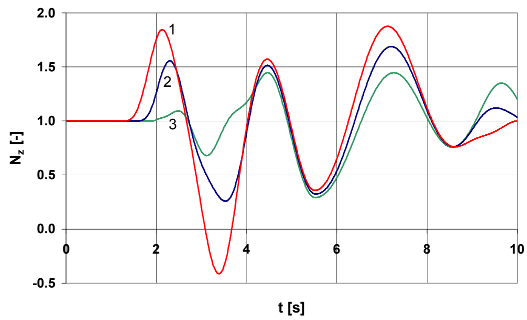

Fig. 3.32 Normal overload $N_z(t)$

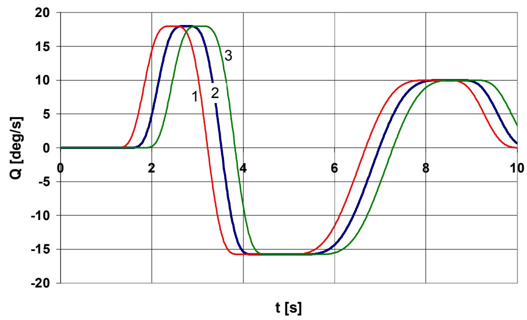

Fig. 3.33 Pitching velocity $Q(t)$

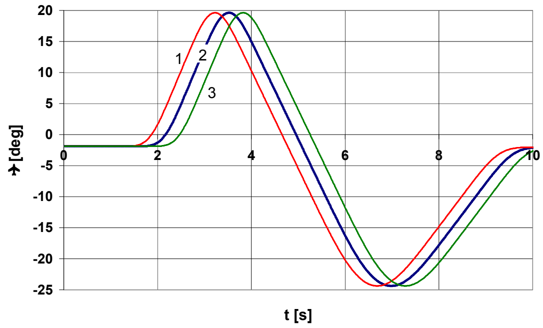

Fig. 3.34 Pitch angle $\Theta(t)$

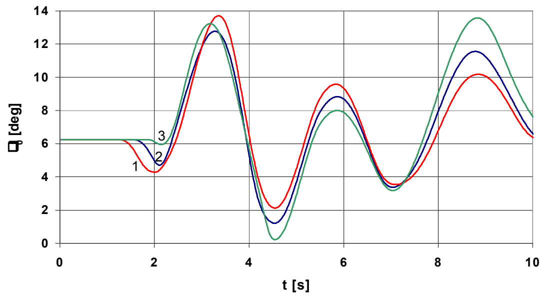

Fig. 3.35 Collective pitch $\theta_0(t)$

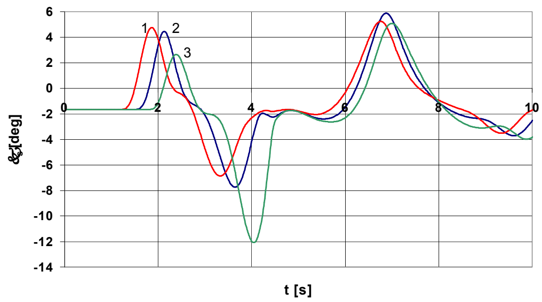

Fig. 3.36 Longitudinal control input $\kappa_S(t)$

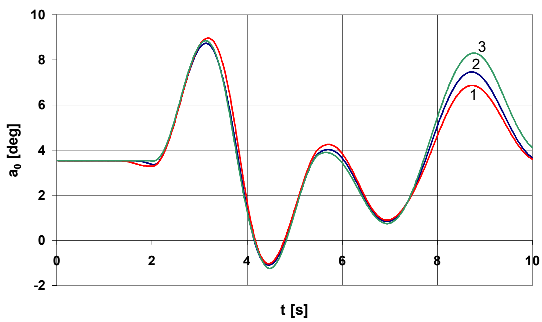

Fig. 3.37 Collective cone angle $a_0(t)$

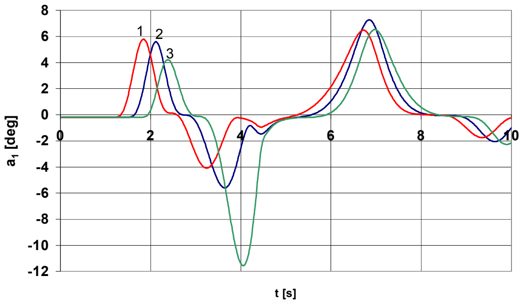

Fig.3.38 Longitudinal cone angle $a_1(t)$

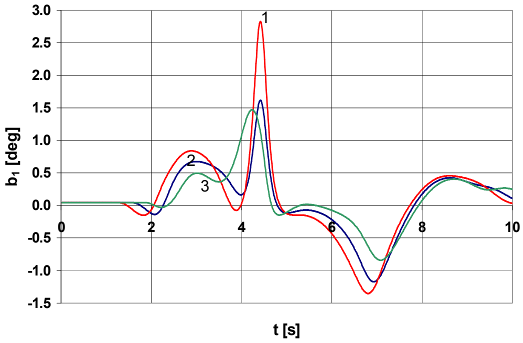

Fig. 3.39 Lateral cone angle $b_1(t)$

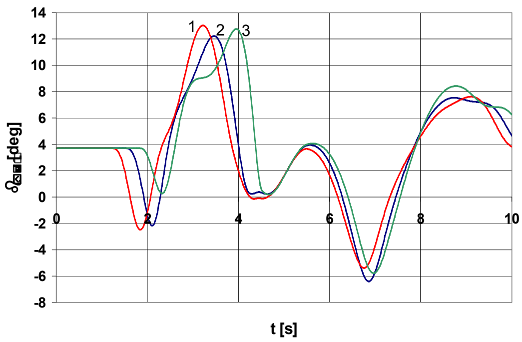

Fig. 3.40 Flapping angle at azimuth 0^0 $\beta_{\psi=0^0}(t)$

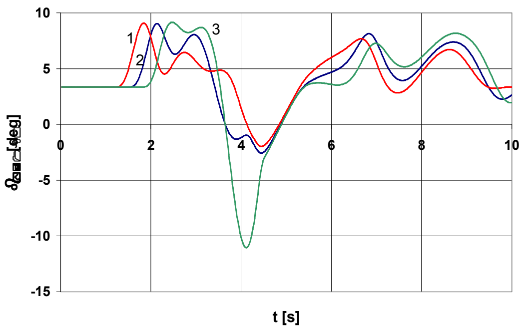

Fig. 3.41 Flapping angle at azimuth 180^0 $\beta_{\psi=180^0}(t)$

3.5. Experimental verification of theoretical analysis

The results of simulation were used for optimisation oh the hurdle-hop manoeuvre. For that purpose a scenario of modified control of the helicopter was worked out. Fig. 3.43 presents

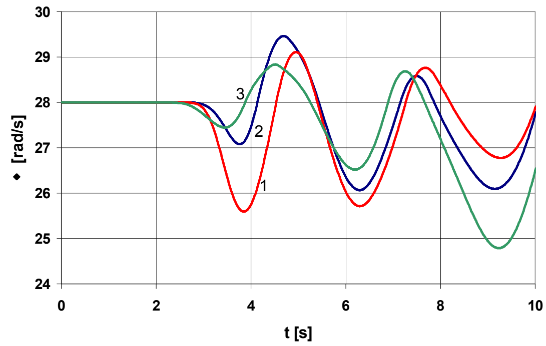

Fig. 3.42 Angular velocity of the main rotor $\omega(t)$

exemplary results. Three trajectories are compared there. The first one shows the manoeuvre performed by a helicopter with a hingeless main rotor. The course has been drawn on the basis of data from literature. The next two curves are obtained for the helicopter with a hinged blades. They are drawn on the basis of the recorded experimental data. The considered cases are classical and modified control.

In every case the main goal is to minimize a overheight of the manoeuvre. One can see that the best results are obtained for the hingeless helicopter. However, as it is seen, a substantial improvement of a hinged rotor helicopter manoeuvrability could be achieved by modification of control. This modification decreases the maximum altitude from 50 meters to 25 meters. The exposition time decreases too.

During test flights /Fig.3.44/ all control and flight parameters were recorded. Next these flights were reconstructed. Figs. 3.45÷3.48 present exemplary results of these flights and simulations.

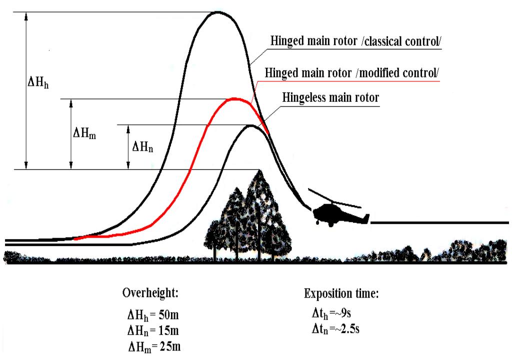

Fig.3.43 Hurdle-hop manoeuvre with minimized overheight

Fig.3.44 Helicopter Sokol performing the hurdle-hop

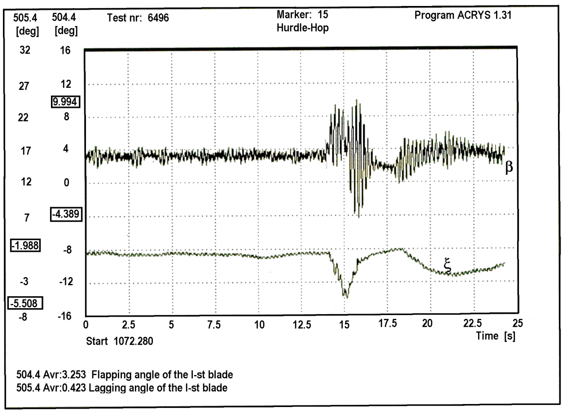

Fig.3.45 Recorded flapping angle of the blade

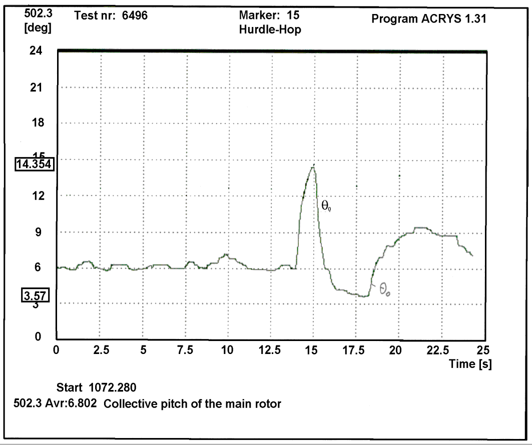

Fig.3.46 Recorded collective pitch

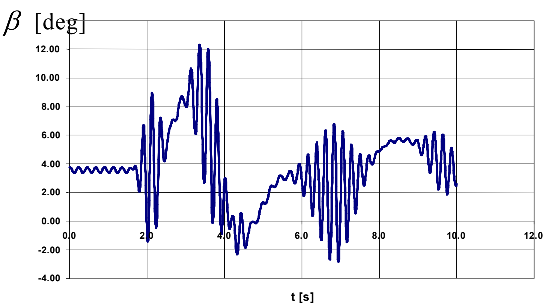

Fig.3.47 Flapping angle of the blade - simulation

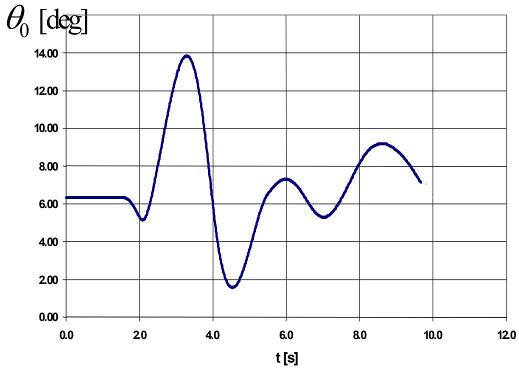

Fig.3.48 Collective pitch - simulation

3.6. Optimisation of NoE manoeuvres – remarks for helicopters' users

As it was shown above, follow the hurdle-hop as an example, each of NoE manoeuvres can be optimised modifying a technique of pilotage. It could improve efficiency and safety of these manoeuvres. On the basis of performed simulations and simulations general remarks for a great deal of manoeuvres have been formulated. Some of these remarks are presented below:

Classical Breaking – performed at low altitude threatens with collision between the tail and blades. This manoeuvre can be modified by a lateral deceleration at the final phase. It causes that the tail is not dropped and a visibility is improved. This modification is possible only for helicopters with engines, which have fast acceleration. In the case of low power acceleration a turnover is possible after too rapid levelling , when the available power is not able to reach the required power.

Hurdle Bypass – the visibility is the most important in the safety point of view. The possibility of pilotage technique modification is minor.

Breaking with Reverse – it is modification of the classical agricultural reverse. It is used to decelerate in front of a hurdle. The collective pitch of the main rotor should be increased in a rolling stage. It allows to increase the deceleration utilising a horizontal component of a thrust. It shortens the way of deceleration.

Hurdle-Hop – modifications depend on the type of the hop, power system features, the type of the main rotor and its work range and the phase of the hop. Two types of the hurdle-hop exist:

1. Altitude maximising is the main goal. It is important in agricultural flights and in the case of unexpected hurdles.

2. Minimising of the exposition time is the most significant in tactical flights because of possibility of flak.

In the case of the low engines' acceleration and the first type of the hurdle-hop it is recommended to accelerate for a few seconds before the beginning of the manoeuvre. It allows increasing the available power to the level required in the next phase of the hop. In the climbing stage a faster increasing of the collective pitch and slower pulling the stick is directed. This stimulates increase of power.

Steering qualities of hinged main rotors are poor when the thrust is small, particularly in the case of negative overload. Therefore it is important to have a suitable thrust in phases, when the helicopter quickly changes its angular position. The thrust supports these changes. This means that the pilot has to increase temporarily the collective pitch directly before the top of the trajectory. This allows to minimize the exposition time.

Minimization of exposition time can also be supported /for helicopters with hinged rotors/ by earlier pitching /negative/ before the top of the trajectory is reached. Simultaneously the collective pitch should be temporarily increased. At the top of trajectory the fuselage should be in horizontal position. Next it is pitching down and the thrust is minimized. The bigger /negative/ is the pitch angle, the shorter is the exposition time. In the leveling phase the pilot should increase the collective pitch in the first stage and next pull the stick. It would be dangerous if he did not increase the thrust first. In this case blades could hit the tail. The excessive increase of the thrust is also hazardous. It can be a reason of a helicopter turnover.

A danger of a main rotor rotation increase arises at the levelling phase of the hurdle-hop. This means that the power is automatically reduced. It may be hazardous for the helicopter with low engines' acceleration if the helicopter have to perform next hurdle-hop, when the high level of power is required. A higher curvature of the trajectory and higher position of the tail are the additional advantages. The hazard of collision between the tail and the ground is smaller.

Dynamic bob up – the first phase is similar to the hurdle-hop. The main task in the second phase is to brake the velocity till the hover. In this manoeuvre the increase of the collective pitch should be more intensive and should start earlier. It allows to keep the hover without a risk of the main rotor rotation growing down – the suitable power is provided. This kind of control at the beginning of this manoeuvre preserves a tail rotor from collision with the ground – the helicopter begin to recede into the distance from the ground without fuselage pitching up. This manoeuvre is efficient for braking in front of the hurdle. The braking way is about 20-30 meters /40-60 for the breaking with reverse/.

4. Concluding remarks

Possibility of the helicopter nap-of-the–earth manoeuvres improvement was presented. It could be done making use of numerical simulations. Their results were the basis of all optimizations. The improved pilotage technique was used and verified in test flights. All the performed investigations showed that execution of NoE manoeuvres could be modified. They were carried out more dynamically but still with a large margin of safety. The used helicopter had a significant reserve of manoeuvrability.

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