Numerical Simulation of Critical and Transient Conditions of Helicopter Spatial Motion and their Adaptation in Flight Tests

A.O. Garipov, A.M. Girfanov, S.A. Mikhailov, and E.I. Nikolaev

A.N. Tupolev Kazan State Technical University, Kazan Helicopters JSC
Kazan, Russia

Annotation

This report considers issues of mathematical simulation of non-steady flight regimes of the helicopter, equipped with hingeless main rotor hub. Also, an idea is given about mathematical simulation of controlled motion of the helicopter. The results given herein are a part of calculations made for Ansat helicopter qualification tests. In addition, an analysis of helicopter capability to perform aerobatic maneuvre is given in this report (normal loop is taken as an example).

Introduction

To perform flight tests there are very high requirements to mathematical simulation of flight operation. First of all concerning flight accident prevention and prevention of helicopter destruction while performing limit maneuvers. Correct solution of this task mostly depends on quality of mathematical models as well as on degree of their adaptation to actual conditions of flight mission. The mathematical model of the helicopter three-dimensional motion, which provides possibility to solve tasks of balance and helicopter flight dynamics, as well as to perform aeroelastic main and tail rotors synthesis, meets such high requirements. To solve balance and helicopter flight dynamics tasks, the mathematical model uses a system of six levels of helicopter equilibrium in space. As physical relations for modeling main rotor blade flexibility Kirchgoff-Clebsch relations are used, they do not limit a value of motion of calculated points. For integration of rotor blade motion equations a decomposition of azimuth blade deformation into Fourier trigonometric series is used. Blade aerodynamic load is computed on the basis of blade element theory using airfoil circular polar. Induced velocities are computed basing on element-impulse theory or disc vortex theory depending on task to be solved. The mathematical model is described more in details in [1]. The use of this model allows pre-planning of flight test thus decreasing the scope of helicopter testing at limit flight conditions.

In addition, it allows performing anticipatory mathematical modeling at the phase of certification tests, thus enabling choose the most optimum helicopter control for required flight conditions and decreasing the number of training flights required for preparation to perform all the steps of the program. One of the goals of the modeling performed is also forecasting of level of load applied on the rotor system units during flights, which cover some items of the test program.

Fig.1. "Ansat" light multi-purpose helicopter

Modeling of rudder pedals reversal in horizontal flight

To prove that the requirements of АП-29 Russian Aviation Rules are met, the flight test program requires performing hovering turns and pedals reversal in horizontal flight. This maneuver should satisfy the following conditions, which are stipulated in the flight test program:

- rate of pedals reversal should not exceed limits specified in Flight Manual;

- angle of steady slip should not exceed a specified value during pedal turn.

The task to be performed by the mathematical modeling was as follows: find such parameters (rate and time) of reversal, at which loads on the helicopter rotor system elements and tail boom do not exceed allowable values.

At the first step, it was analyzed how helicopter airspeed affects the value of slip angle maximum amplitude with tail rotor pitch changing at constant rate.

At low airspeed slip angle is determined by a relation between main rotor torque and tail rotor thrust moment. With airspeed increasing aerodynamic forces, generated by vertical empennage and fuselage, are also increasing.

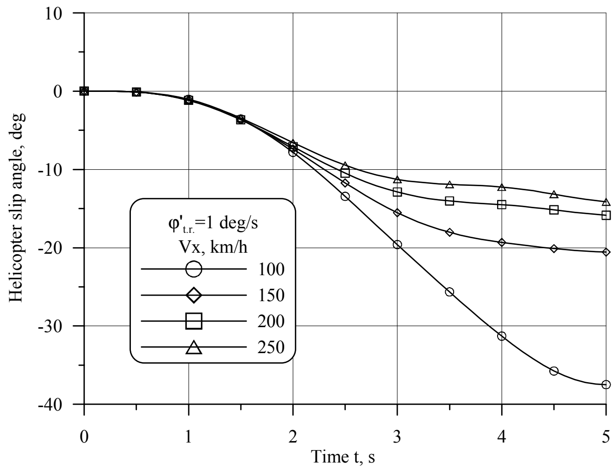

Fig. 1. Helicopter slip angle

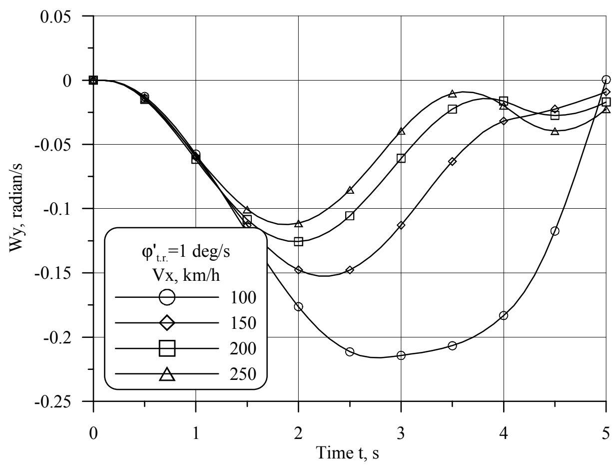

Fig. 2. Angular velocity of helicopter rotation

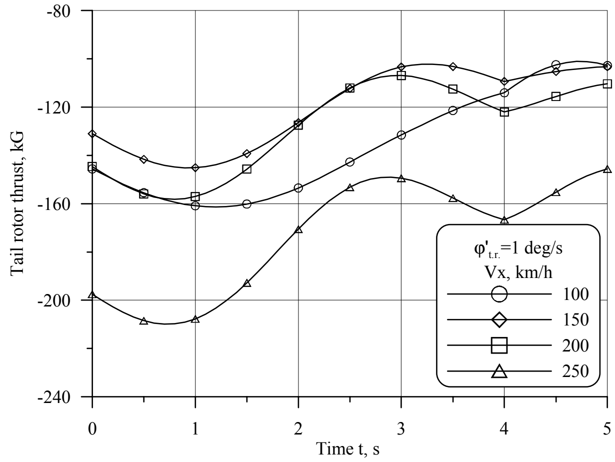

Fig. 3. Tail rotor thrust

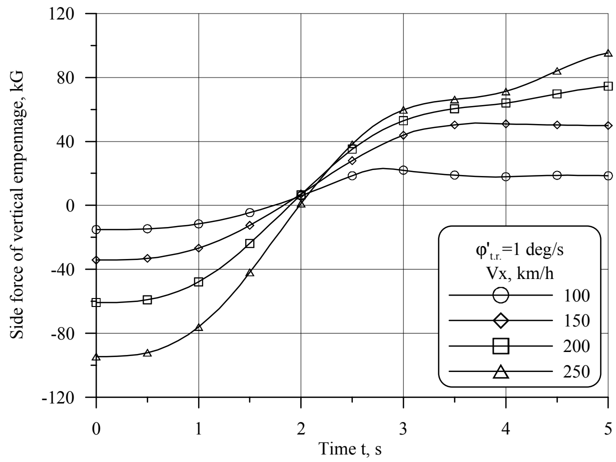

Fig. 4. Side force of vertical empennage

The results given herein show that with the rate of tail rotor pitch change being constant, the airspeed is the main factor, which affects the value of the helicopter slip angle and with airspeed increasing, the helicopter oscillation amplitude is decreasing.

At the second step, a design modeling of light conditions with various rate of tail rotor pitch change was performed for airspeed of 100 and 250 km/h.

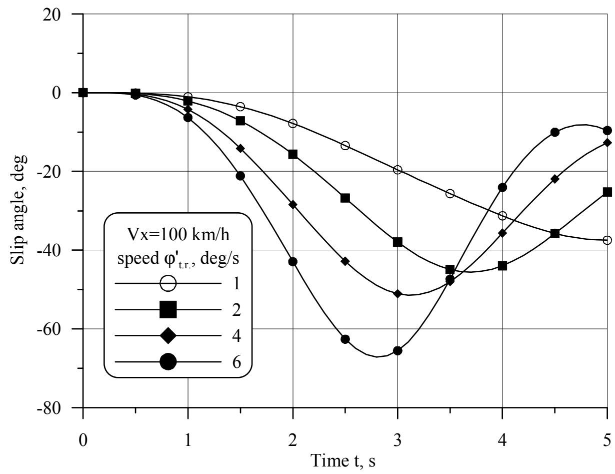

Fig. 5. Slip angle (V=100 km/h)

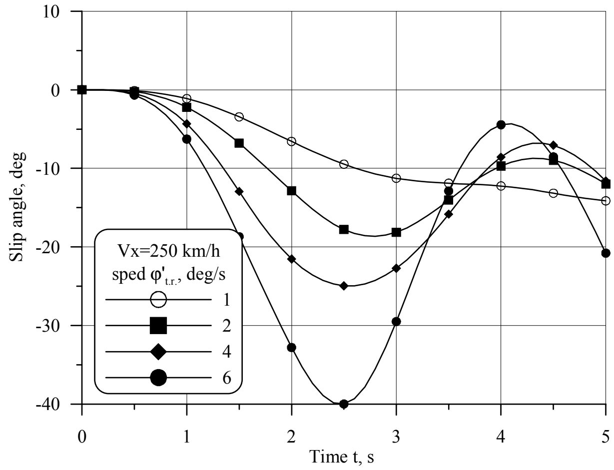

Fig. 6. Slip angle (V=250 km/h)

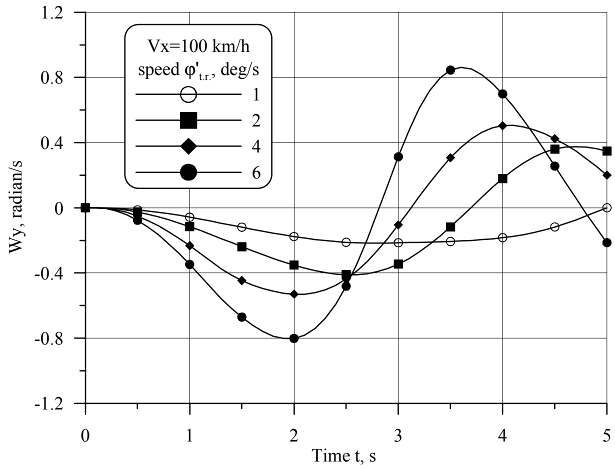

Fig. 7. Angular velocity of helicopter rotation (V=100 km/h)

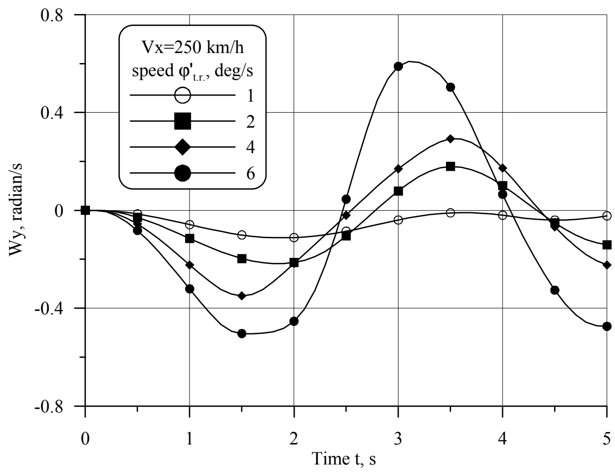

Fig. 8. Angular velocity of helicopter rotation (V=250 km/h)

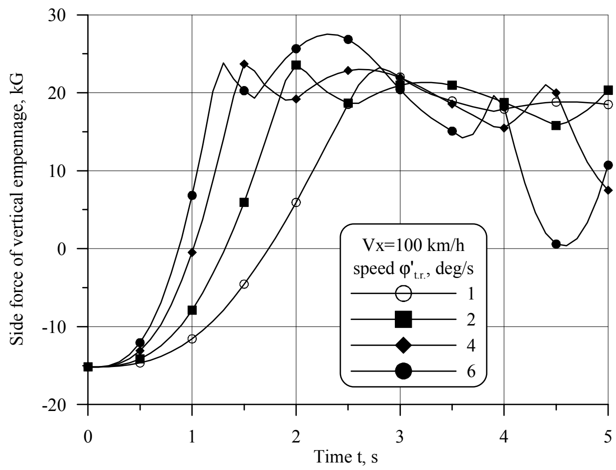

Fig. 9. Thrust of vertical empennage (V=100 km/h)

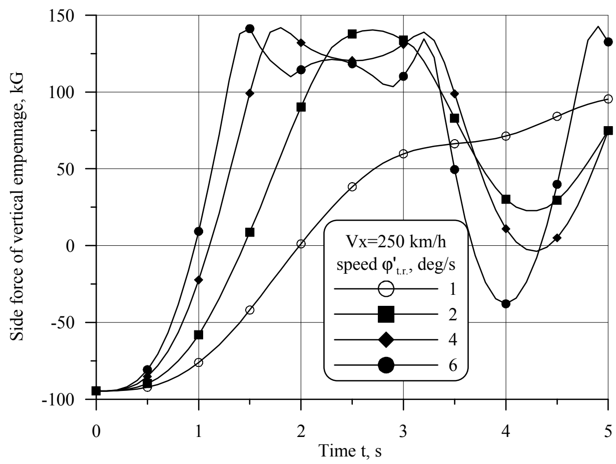

Fig. 10. Thrust of vertical empennage (V=250 km/h)

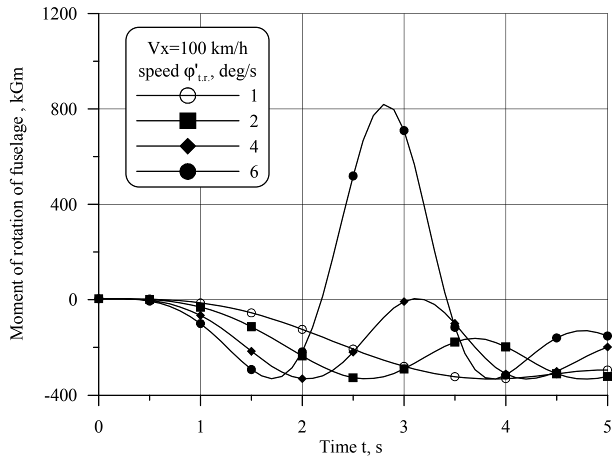

Fig. 11. Moment of rotation of fuselage (V=100 km/h)

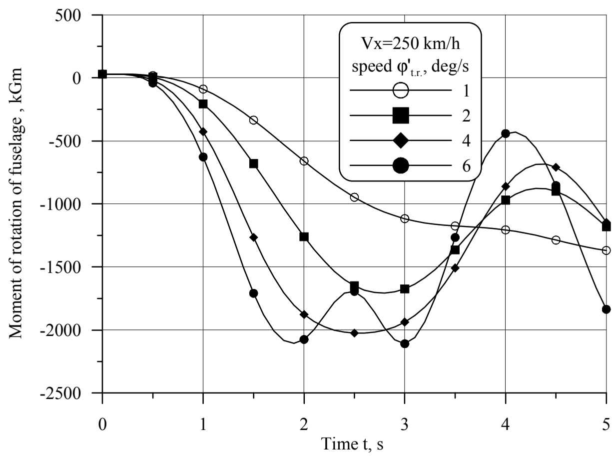

Fig. 12. Moment of rotation of fuselage (V=250 km/h)

With increasing rate of collective pitch change the slip angle oscillation amplitude is increasing. At airspeed of 100 km/h the slip angle exceeds 60 degrees, this results in change of the sign of M_y fuselage, in addition, at such great slip angles the vertical empennage is getting into a zone of stalled flow. At airspeed of 250 km/h there is no change of the sign of M_y fuselage, but this is possible with further increasing of rate of tail rotor pitch change.

Then a computation of non-steady slip condition with pedals reversal at airspeed of 125, 175, 225 and 250 km/h was performed (ISA, at altitude of 500 m).

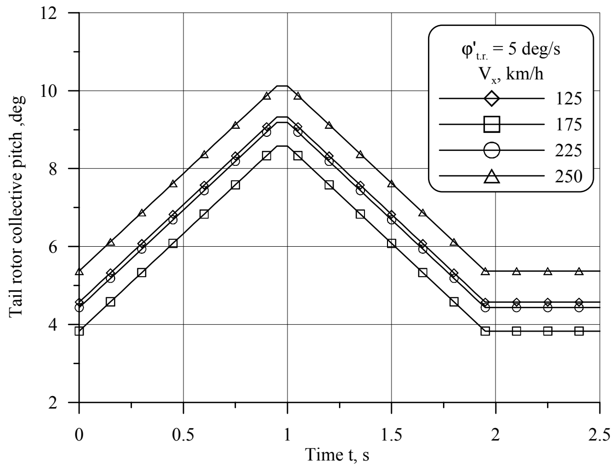

Fig. 13. Tail rotor collective pitch law

The following tail rotor pitch law was taken:

- 0÷0.95 s range, tail rotor pitch linear increase at a rate of 5 degrees/s (initial tail rotor pitch corresponds to trim value);
- 0.1 s tail rotor pitch keeping;
- 1.05÷2 s range, decrease of collective pitch at a rate of 5 degrees/s up to trim position.

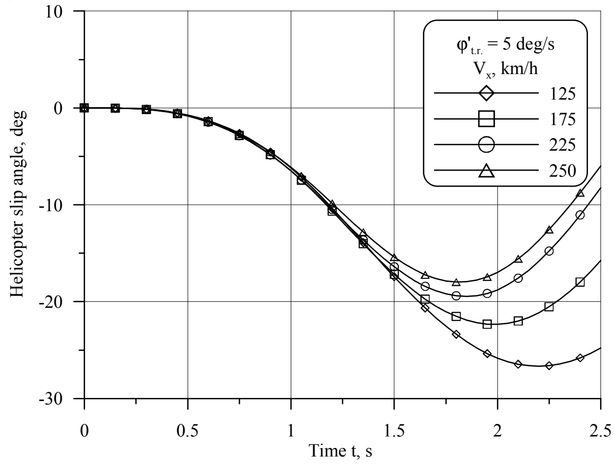

Fig. 14. Helicopter slip angle

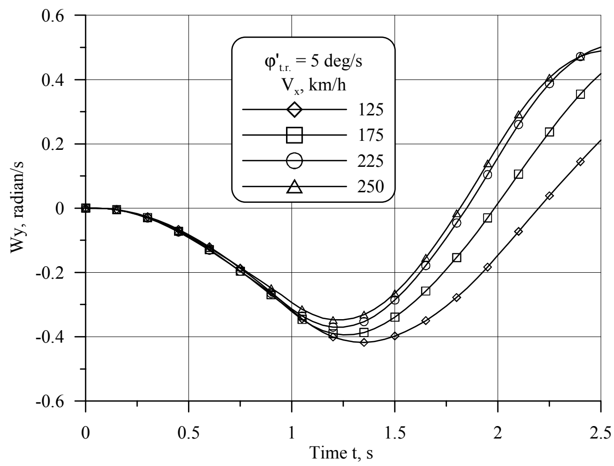

Fig. 15. Angular velocity of helicopter rotation

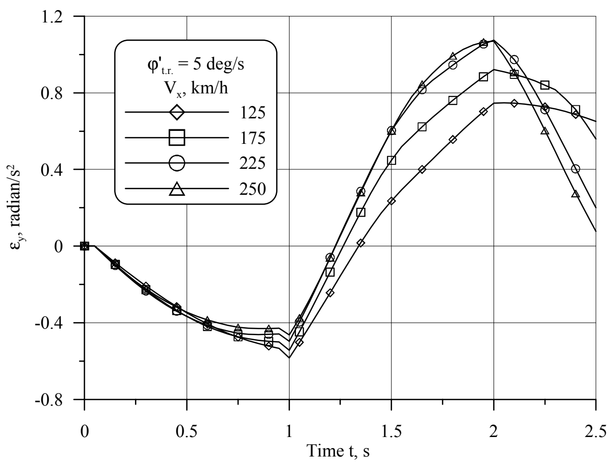

Fig. 16. Angular acceleration of helicopter rotation

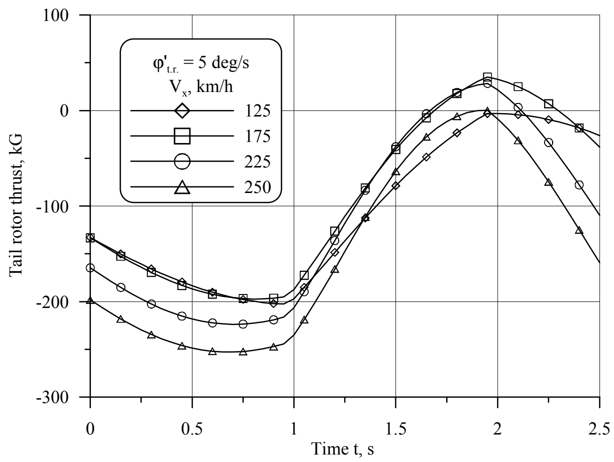

Fig. 17. Tail rotor thrust

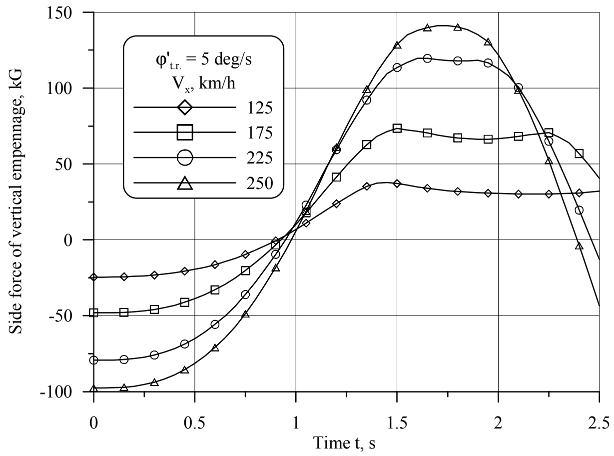

Fig. 18. Side force of vertical empennage

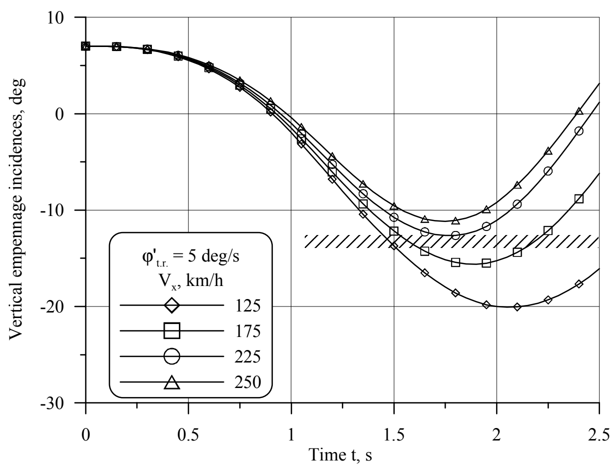

Fig. 19. Vertical empennage incidences

The analysis of the computation results allows making a conclusion that a maneuver performed at a speed of 225 km/h meets the requirements:

- maximum value of slip angle will not exceed 20° (Fig. 14);
- angle of steady slip at $\varphi_{рв}$ =10° will be about 15°;
- typical zones of maximum angular velocity and acceleration are within 2-second zone;
- vertical empennage incidences are not within stalled flow zone.

Determination of maximum allowable overloads

To substantiate that the helicopter structure meets the requirements of АП-29 Russian Aviation Rules it should be proved by calculations and experimentally that it is impossible that overload, which the helicopter is designed for, can occur in flight.

According to this requirement, maximum possible "operating" overloads were received as a result of modeling of such maneuvers like dive recovery and steep climb within limitations specified in Flight Manual.

To solve this task a 3-D model of helicopter flight was used. The main rotor blades are considered being elastic in flexure (in two planes) and in torsion.

Maximum possible "operating" overloads were determined for helicopter minimum take-off weight and average CG position. A modeling of diving from the altitude of 700 m with a pitch angle of 20° maximum and with speed reached at diving recovery within 120-250 km/h has been performed. At the same time main gear box shaft loads should not exceed limits. At altitude of 400-500 m smooth entry into steep climb with a pitch angle of 20° within initial speeds range of 120-250 km/h was modeled. When an angle of 20° is reached, steep climb recovery is performed. Maximum rate of pitch change is equal to 5 degrees/s for both cases as required by Flight Manual.

To evaluate possible solutions of this task, a pitch angle idealized trajectory (third degree polynomial) with an equivalent rate not exceeding 5 degrees/s was plotted. Total time of maneuver with a pitch angle changing from –20 up to +20 degrees is 8 seconds. For idealized trajectory the maximum value of the helicopter angular velocity is 6.875 degrees/s. Having determined angular accelerations and having multiplied them by the moment of inertia of helicopter, we get a difference between main rotor torque and fuselage moment ΔM_z, which should be maintained for desired trajectory.

There were considered three variants of modeling of "diving recovery with entry into steep climb" provided maximum thrust is reached at speed of 250 km/h. Diving at speed of V_x = 235 km/h V_y = –6.3m/s is an initial reference point.

Variant 1. Trajectory with insignificant pitch angle fluctuations relative to idealized line. Quality controlling parameters, in this computation, correspond to flight ones. Maximum main rotor shaft moment is received at the beginning and at the end of maneuver at the points, where the sign of pitch angle time first-order derivative is changed. Power required is at its limit, even slightly exceeded in maximum zone.

Variant 2. «Undershoot» – failure to reach the point with a pitch angle +20 degrees. This occurred because of delay of decreasing of longitudinal angle of incidence of the swash plate by ≈1.3 seconds. This delay resulted in significant increase of fuselage moment into negative. This rides on high rate of climb V_y =30 m/s of the light helicopter. Therefore the angle of attack of the fuselage passed into zone of negative angles of attack and a great diving moment appeared, consequently the angular velocity exceeded 11 degrees/s, and sudden decrease of pitch angle value occurred.

Variant 3. «Overshoot» – attempt to increase suddenly main rotor collective pitch up to 14 degrees. With this controlling action significant increase of main rotor hub moment occurred, this resulted, after a small time period, in increase of angular velocity. When angular velocity exceeds 11 degrees/s, helicopter pitch angle is increasing avalanche-likely and angles of attack of fuselage and empennage passed into positive zone.

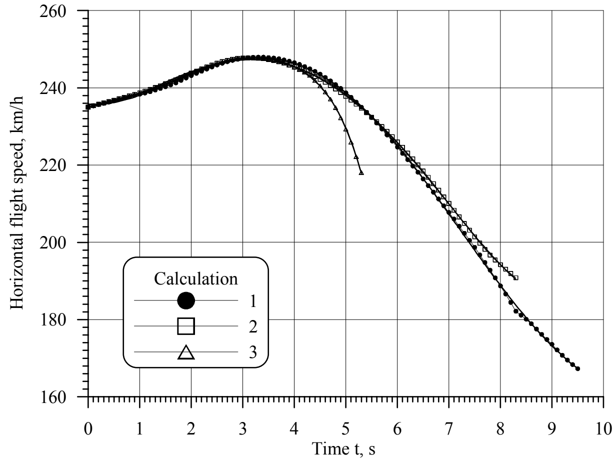

Fig. 20. Horizontal flight speed (in Earth-fixed coordinate system)

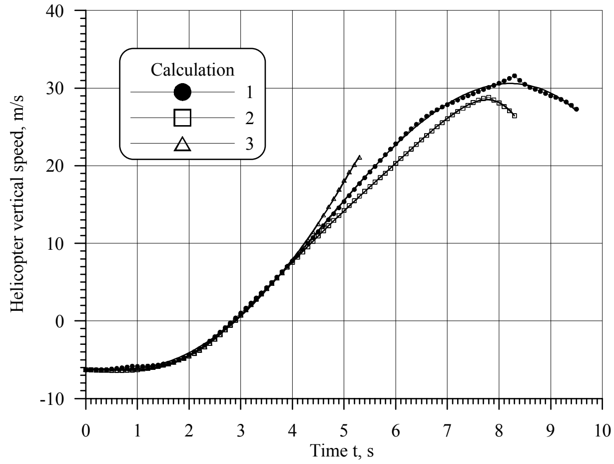

Fig. 21. Helicopter vertical speed (in Earth-fixed coordinate system)

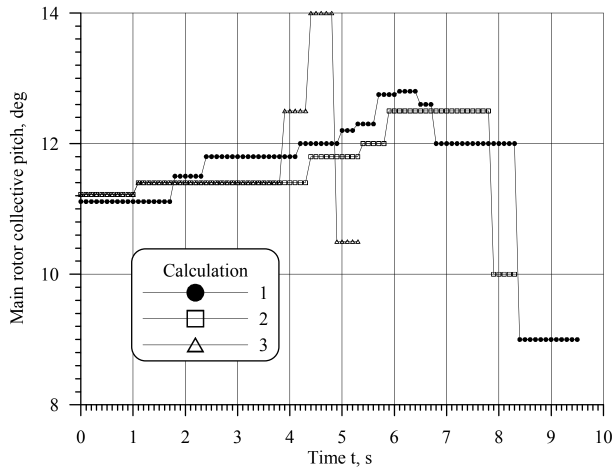

Fig. 22. Main rotor collective pitch

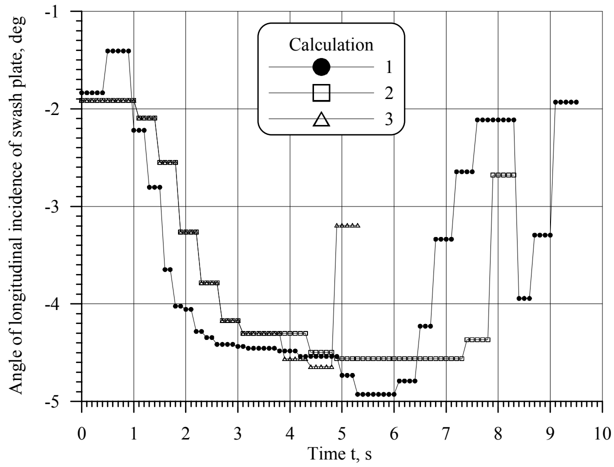

Fig. 23. Angle of longitudinal incidence of swash plate

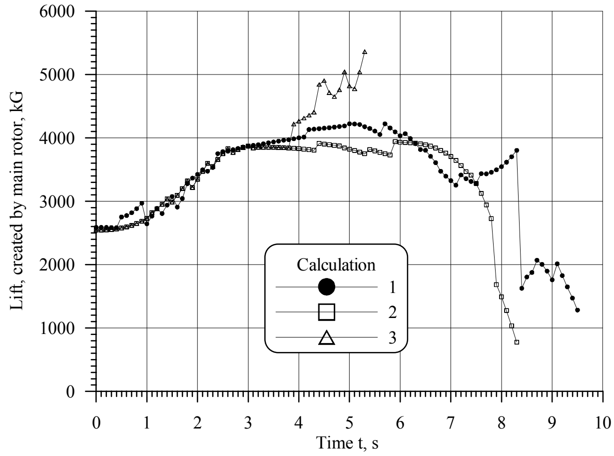

Fig. 26. Lift, created by main rotor

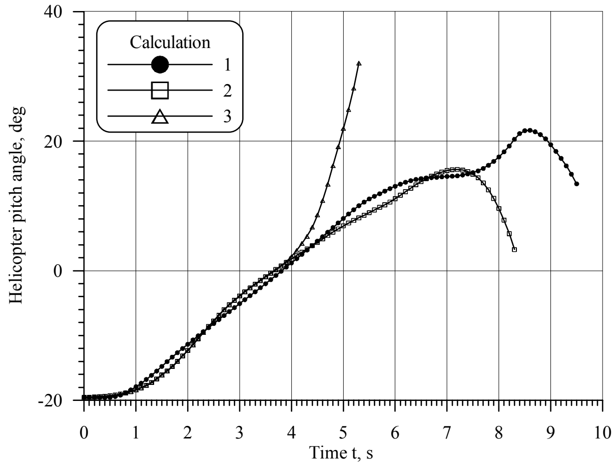

Fig. 24. Helicopter pitch angle

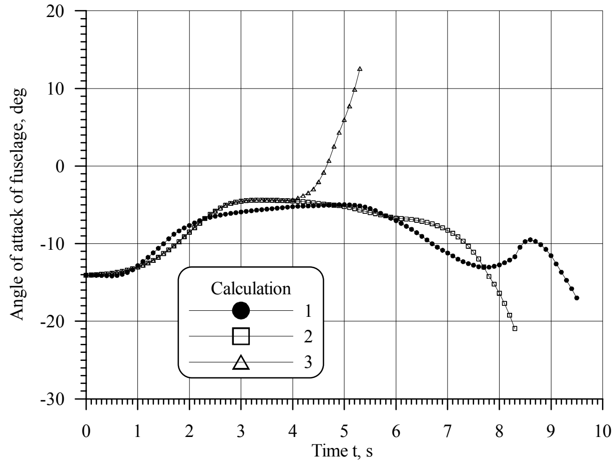

Fig. 27. Angle of attack of fuselage

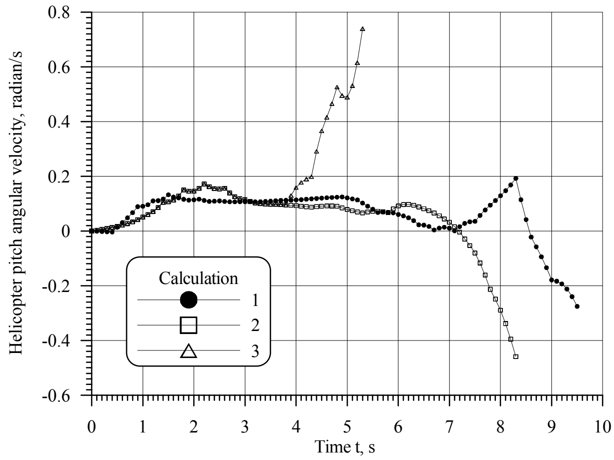

Fig. 25. Helicopter pitch angular velocity

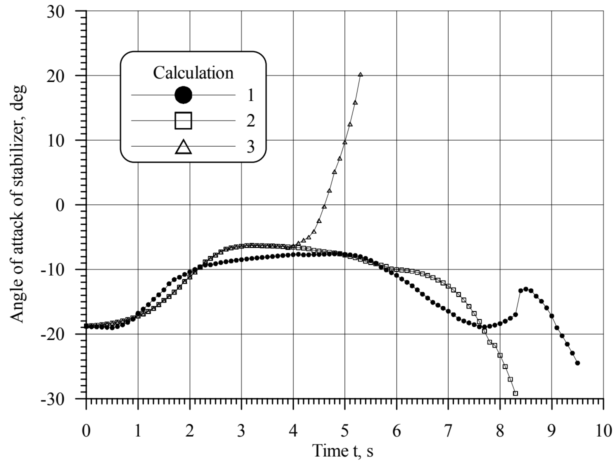

Fig. 28. Angle of attack of stabilizer

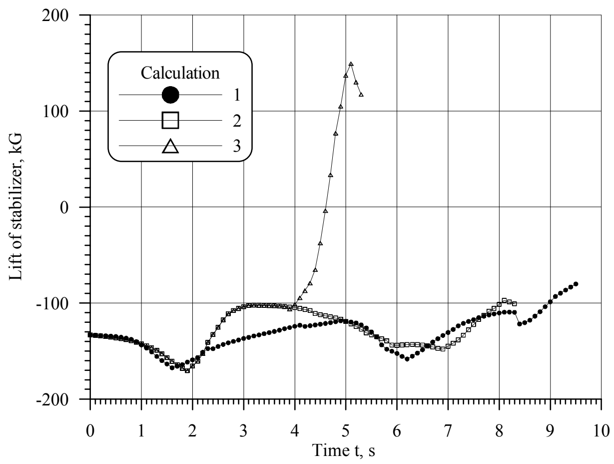

Fig. 29. Lift of stabilizer

Upon the results of computation described here above a conclusion can be made: in first variant the flight trajectory is close to desired, with insignificant fluctuations of pitch angle relative to idealized line. This is caused by fluctuations of angular velocity within 6.875±4.01 degrees/s (momentary maximum 10.9 degrees/s). According to this computation the value of maximum thrust is equal to 4300 kg. In practice, there can be a lot of combinations of V_x and V_y with controlling parameters in such a maneuver. Therefore, this value can not be uniquely called as a maximum and additional computation is required.

Modeling of normal loop

In principle, the helicopter can perform aerobatic maneuvers in horizontal and vertical planes. However, to do it the helicopter should have a good maneuverability, great available power and its structure should withstand overload generated during maneuvers.

Utility helicopters have relatively little available power, therefore the number of authorized maneuvers and somersault for these helicopters is not so great, the maneuvers authorized are: turns, spirals, steep climb, turn during steep climb etc.

One of the most difficult aerobatic maneuvers is "normal loop". This maneuver is limited by thrust of main rotor and by the helicopter maneuverability characteristics. Therefore simulation of this maneuver requires proper approach to solution of the helicopter 3-D motion equations.

The helicopter flight trajectory during "normal loop" maneuver has a form of a vertically stretched circle. This is connected with intense deceleration on the ascent portion of the loop and acceleration on its descent portion.

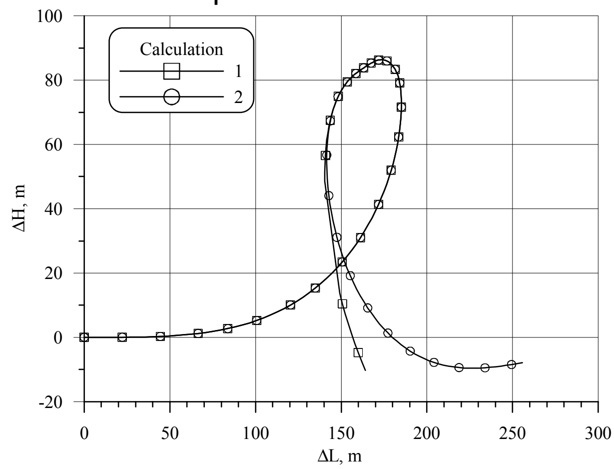

Fig. 30. Helicopter flight calculated trajectory

For piloting the most difficult portion is the second one - descent portion of the loop. Insignificant slow-down of the pilot's action results in significant speed increase. And the vertical overload is increasing as well. An attempt to stop its increasing by decreasing pitch angular velocity results in more intensive acceleration of the helicopter.

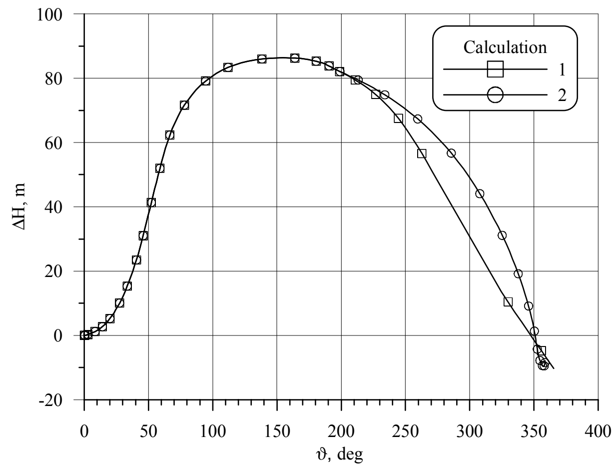

Fig. 31. Pitch angle versus altitude

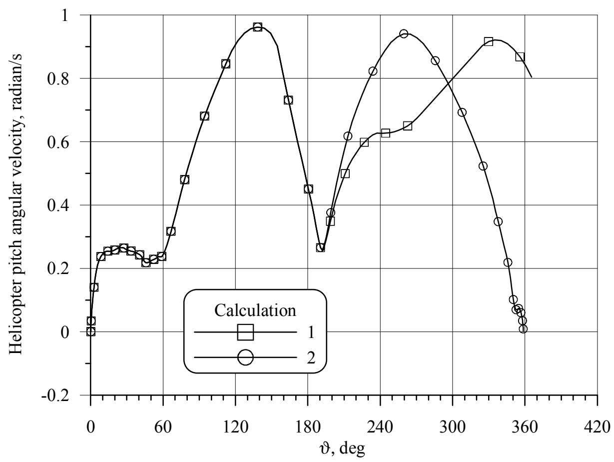

Fig. 32. Helicopter pitch angular velocity

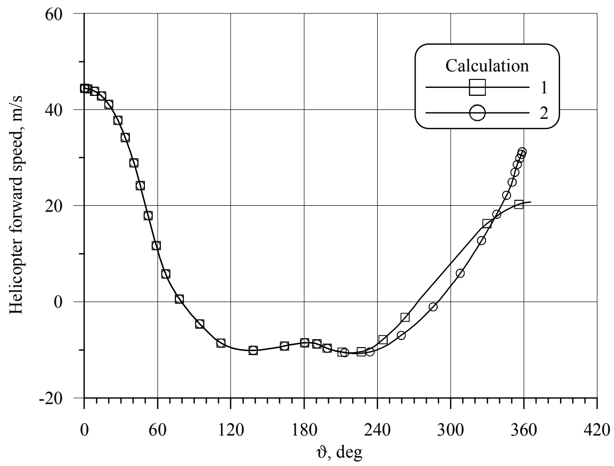

Fig. 33. Helicopter forward speed

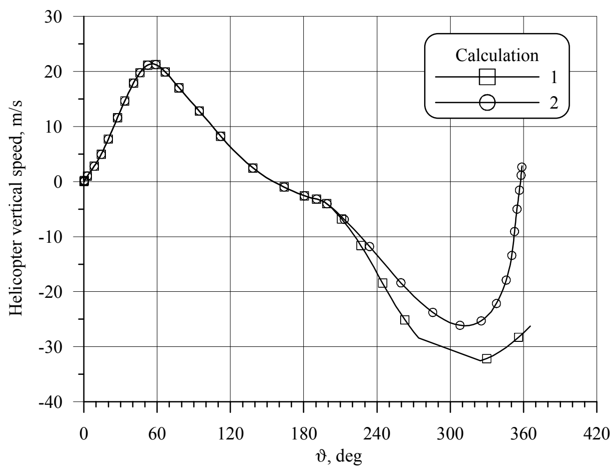

Fig. 34. Helicopter vertical speed

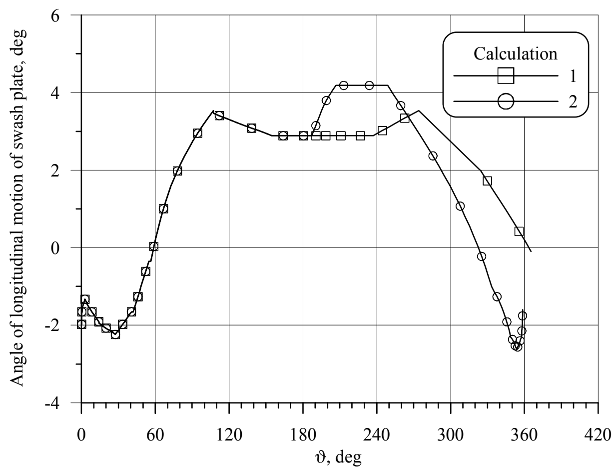

Fig. 35. Angle of longitudinal motion of swash plate

Reference

1 Modelling non-steady flight regimes of a hingeless rotor helicopter A.O. Garipov, A.M. Girfanov, S.A. Mikhailov, and E.I. Nikolaev

2. A.M.Girfanov, S.A.Mikhailov, and E.I.Nikolaev, “Study of the effect hingeless main rotor elastic blades on torsion loading”, Proceedings of the Russian Helicopter Society IV-th Forum, Moscow, 2000.

3. W. Johnson, Helicopter Theory, in two book, [Russian translation] Vol. 1, Mir, Moscow, 1983.

4. A.S.Braverman and A.P. Waintraub, Helicopter Dynamics. Limiting Flight Regimes, Mashinostroenie, Moscow, 1988.

5. V.A. Kozhevnikov, Automatic Stabilization of Helicopters, Mashinostroenie, Moscow, 1978.

6. A.P.S. Bramvel, Helicopter dynamics, [Russian translation], Mashinostroenie, Moscow, 1982

7. A.M.Girfanov, Aeroelastic calculation and balancing of a single-rotor helicopter with a hingeless main rotor, Candidate of technical sciences dissertation, Kazan, 2000.