Aerodynamics and Flight Dynamics of Aircraft in Vortex Wake of Helicopter

Victor A. Anikin[1], Boris S. Kritsky[2], Veniamin A. Leontiev[3]

[1]Kamov Company
8 the 8th March Str. Lubertsy, 140007, Moscow Region, Russian Federation
e-mail: kb@kamov.ru

[2]Air Force Engineering Academy named after prof. N.E. Zhukovsky
3 Planetnaya Str., Moscow, 125190, Russian Federation
e-mail: kritsky@starlink.ru

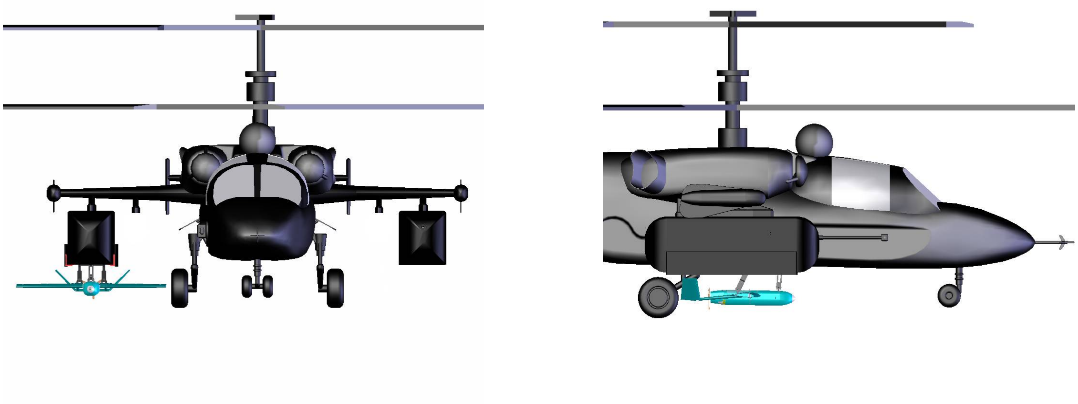
[3]Central Aerohydrodynamic Institut named after prof. N.E. Zhukovsky
1 Zhukovsky Str. Zhukovsky, 140180, Moscow Region, Russian Federation
e-mail: taurus2@serpantin.ru

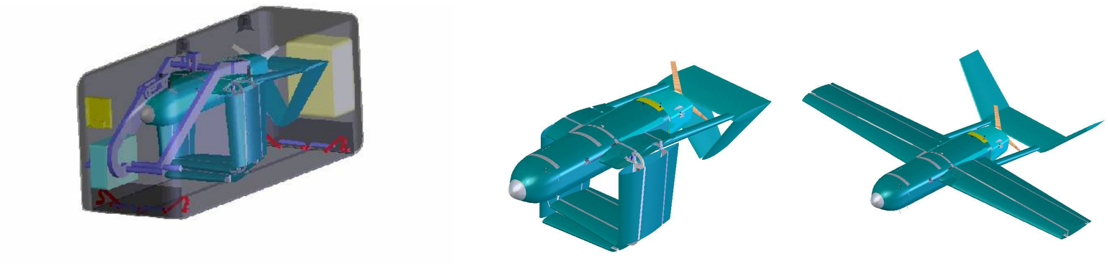
Key words: Aerodynamics, dynamics, modeling, aircraft, vortex wake.

Abstract: Special features of aerodynamics of aircraft near by a main rotor of a helicopter are examined. The description of linear and nonlinear free vortex structures of the main rotor and fields of disturbance velocities are given. Stationary and non-stationary aerodynamic characteristics of the aircraft are discussed during its motion in immediate proximity of the main rotor of the helicopter. Dynamics of motion of the aircraft in a strongly disturbed environment generated by the main rotor and influence of its parameters on the character of motion are modeled. Examples of numerical realization of aircraft motion near by the main rotor of the helicopter are presented.

INTRODUCTION

To perform different missions of monitoring (including examination of dangerous areas for man) a transportation system incorporating carrier-helicopter with unmanned air vehicle of aircraft type (UA) which is located on it may be proposed. The carrier delivers UA into a prescribed region and fulfills its launching. Information accumulated by UA is transmitted on board of helicopter and processed. If necessary, it is transmitted to control point. After performing the mission, the carrier takes UA and transports it to the base. The advantages of such a system are a large area of the Earth surface under examination per time unit and a relative cheapness of the work performed. UA may be transported in a standard container (used in helicopters) in folded up condition (Fig.1). The launch from the container may be automated. The use of a two-seat helicopter is the most rational with the first pilot performing helicopter piloting and the operator controlling UA and collecting data.





Standard container Scheme of folding up Aircraft configuration

Figure1: Arrangement of UA on helicopter

Problems of launch

At present aerodynamics of a low-speed flying vehicle moving in a disturbed flow generated by the main rotors is studied insufficiently. The aim of the work presented is to carry out preliminary studies making it possible to answer the question about the conditions and implementation of air launch.

Complicated disturbed motion of flying vehicle under action of the main rotor system is connected with the following problems:

1. Complicated disturbed flow generated by the main rotor system of helicopter;
2. High flow non-uniformity and considerable values of induced velocity components along flying vehicle trajectory;
3. Separated flow over a flying vehicle;
4. Considerable unsteadiness of flying vehicle aerodynamics;

Let consider these problems.

Figure 2 shows the visualization of a vortex structure of the main rotor system of a single-rotor helicopter (Fig.2a) and upper (Fig.2b) and lower (Fig.2c) rotors of a coaxial helicopter in regimes of flight with low relative speeds. It is seen that a flow generated by the main rotor system is of a complicated character.

a b c

Figure *2: Visualization of a vortex structure of the main rotor system*

Different theories are used to compute the velocities induced by the main rotor in an arbitrary point of space. In the case under consideration the most interesting is a simple, well developed quasi-linear disk theory using a design scheme of a skewed vortex cylinder [1]. This theory makes it possible to estimate average in time velocities induced by the main rotor with adequate accuracy. In Figure 3 compared are design and experimental average induced velocities at the points corresponding to possible aircraft trajectory (the points are at different distances from the main rotor plane $\bar{y}$ = -0.05, -0.2 and different azimuths ψ =45º÷335º) Calculated values are characterized by satisfactory accuracy.

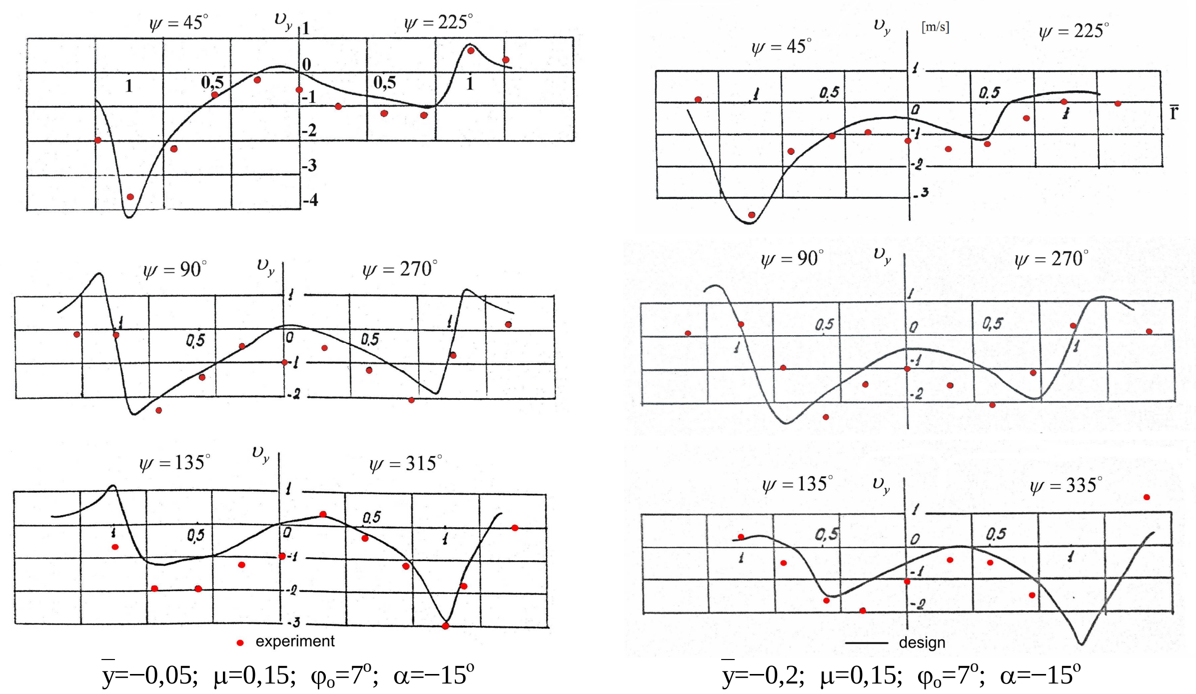


Figure 3: Comparison of design and experimental average induced velocities

Considered is a range of relative speeds of flight within which a main rotor will greatly influence UA.. The speed range corresponds to UA location inside a vortex cylinder of the main rotor.

Figure 4 shows the relation between the vortex cylinder angle of inclination and relative speed of flight. In the range of low relative speeds of flight $0 \le \mu \le 0.15$ ($0 \le V \le 100$ km/h) UA is inside the vortex cylinder and is greatly influenced by the main rotor.
On the other hand, it is difficult to control air launch at the air speed of $V \le 50$ km/h (unstable operation of the speed indicator). Therefore, for the analysis, a range of launching speeds of $50 \le V \le 120$ km/h may be selected.

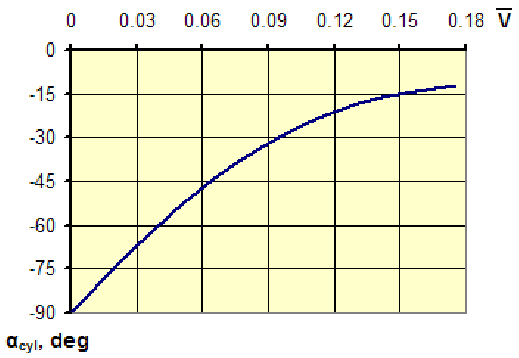


Figure 4: Relation between the vortex cylinder angle of inclination and relative speed of flight

Let consider vertical induced velocity change along the longitudinal OX axis at the distance of y=0.7 m below the plane of the left wing for three computed sections z=1.9, 2.7, 3.5m that correspond to the UA plane of symmetry and middle parts of UA outer wing (Fig.5). In Figure 6 given are the relations computed for three speeds of flight V=50, 80km/h. A strong change of vertical induced velocities along the OX axis is observed, especially in the vicinity of the vortex cylinder boundary. Besides, it is seen that the boundary of the vortex cylinder approaches UA and the value of induced velocity reduces with the increase of flight speed.

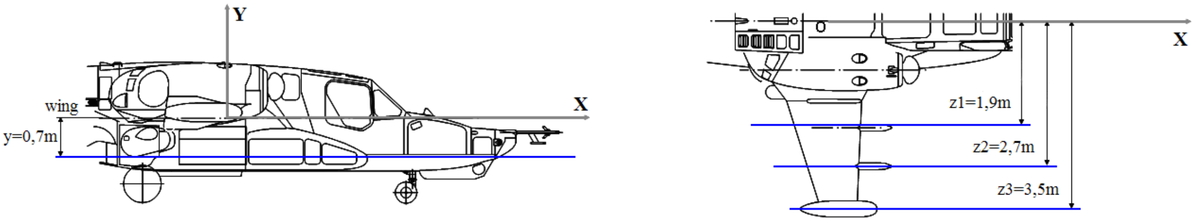
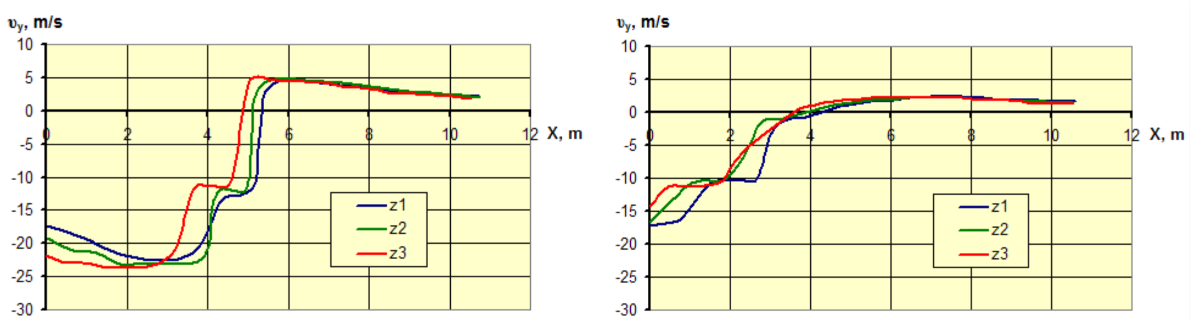


Figure 5: Computed sections



V=50 km/h V=80km/h

Figure 6: Change of vertical induced velocity

The pattern of changing the values of vertical induced velocities along the span of the wing over the OZ axis is not so visible.

Some peculiarities of the rotor influence on UA at low flight speeds can be marked:

- high inflow angle and stall at UA lifting surfaces;
- great gradient of changing the vertical velocity near the boundary of the vortex cylinder (strong influence on flight dynamics when crossing this boundary).

With the increase of speed the above peculiarities weaken. At speeds more than 100km/h they become negligibly small.

Let consider the effect of unsteadiness of disturbed flow on UA motion. To estimate it, computations have been carried out on the basis of the unsteady nonlinear theory [2]. Main principles of the theory are as follows. The main rotor blades, other lifting surfaces are replaced by thin base surfaces (Fig.7). The medium is assumed to be non-viscous and incompressible. The flow outside the surfaces and their wakes is potential. In this case several conditions are met: boundary condition of no penetration onto S_i surfaces, condition on lacking pressure difference in vortex sheets σ_j, Kutta-Zhukovsky hypothesis of finite velocities at edges L_i, condition on attenuation of disturbances at infinite distance from the rotor and its wake. Continuous processes and distributions are replaced by discrete. Blades and other lifting surfaces are simulated with vortex frames, while a continuous in time process of changing the boundary conditions and flow parameters is replaced by a stepwise. The values of kinematical parameters remain unchanged within one temporal step. At each temporal step, beginning from the first one, after solving the system of linear algebraic equations, the strength of all vortex frames of the blades and the wake behind them are defined. This strength enable determination of the blade loads by using the Cauchy-Lagrange integral. Distributed and total characteristics of the rotor are defined by summing aerodynamic loads distributed by panels. The configuration of the vortex wake is defined during solving the system of equations.

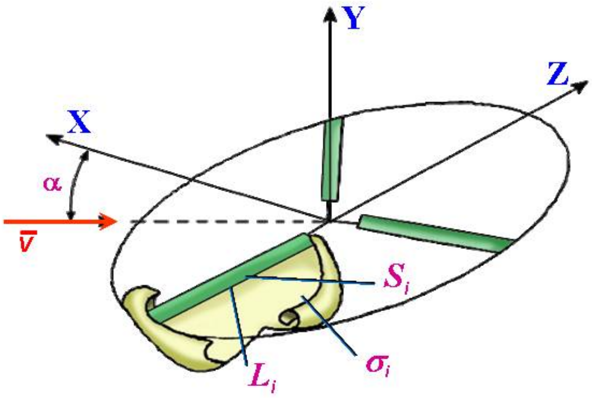


Figure 7: Replacement of main rotor blades by thin base surfaces

Vortex structures of the rotor derived in flight tests and computed by using the non-linear unsteady theory are compared in Fig.8. Their qualitative and quantitative closeness is seen.

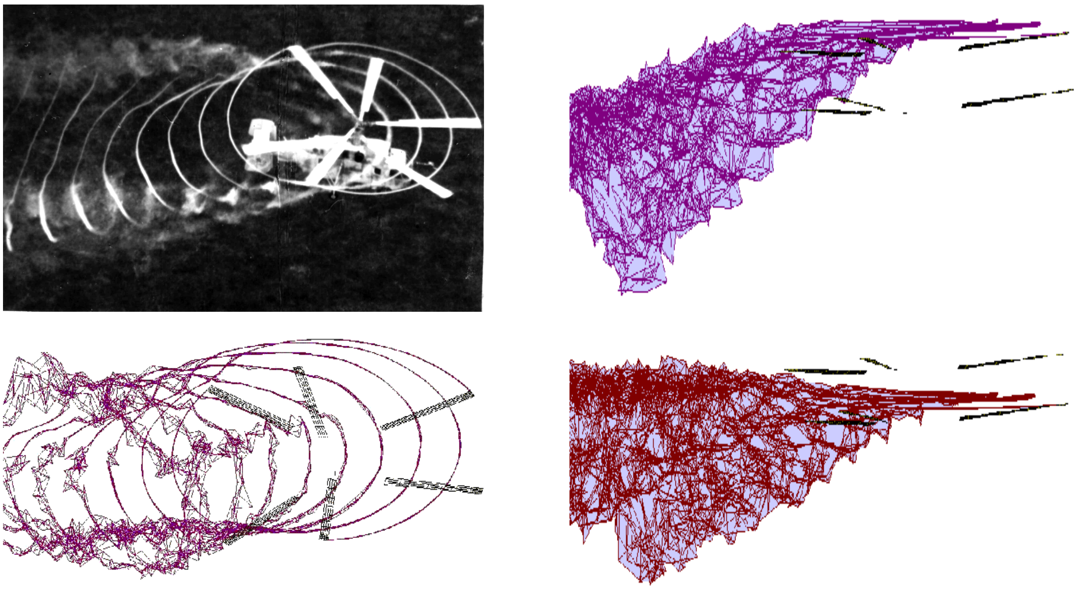


Figure 8: Vortex structures

Simulation of the flow around UA moving in the main rotor stream [2] has revealed that unsteady fluctuations of the aerodynamic load of UA are of a high-frequency character. In Figure 9 shown is the change of the lift of UA moving in the rotor stream with the acceleration of a=4.42 m/s^2 and angle of attack to undisturbed flow of 6º. Maximum amplitude of oscillations is about 2kg. Such the amplitude and frequency of aerodynamic load fluctuations will not result in a noticeable unsteady shift of the UA center of mass. They will only cause vibrations in UA. Therefore it is reasonable in this case to use stationary aerodynamic characteristics in solving the tasks of flight dynamics. This confirms the possibility of applying average in time induced velocities, i.e. to operate within quasi-linear disk theory.

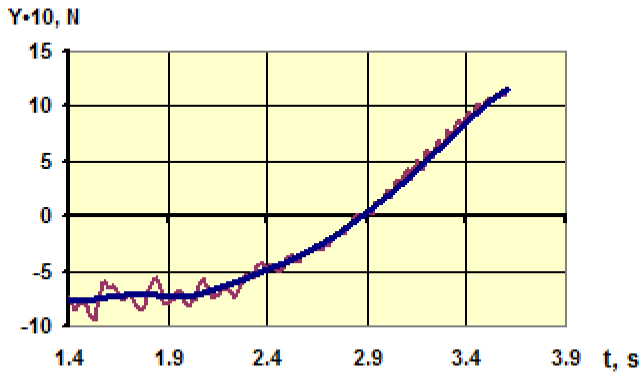


Figure 9: Change of the lift of UA moving in the rotor stream

Let study disturbed motion of the UA when it is launched from the helicopter.

Mathematical models

It is necessary to compute relative motion of the UA about the helicopter from the moment of its launch up to time when the relative air track of the UA towards the $O_B X_B$ axis will become more than the main rotor radius.

In this case the motion of aircraft of a "classic" configuration should be considered at initial (launching) speeds of flight 50, 75, 100 and 125km/h. The aircraft takes off the left outer wing of the helicopter in trim mode at one of the above speeds of flight at the altitude of 100m under ISA conditions with operating propeller delivering the thrust of 25kg.
A helicopter with takeoff mass of 10000kg is considered as a carrier. An aircraft with mass of 50kg is at the distance of y=0.7m below the plane of the left wing. Its center of mass is shifted by the distance of z=-2.7m about the helicopter plane of symmetry.

The aircraft motion should be computed with due regard for the influence of the helicopter. As there are no available experimental data about the effect of the helicopter airframe on the aircraft, it is assumed at this stage of work that this effect is absent.
The problem is being solved as follows: at the initial moment of time the trim of the helicopter with strictly fixed aircraft is computed. Then the separation takes place and the computation of a disturbed aircraft motion is carried out, provided that the helicopter remains in trim mode.

Mathematical description of the UA motion in the vicinity of a rotorcraft will entail great difficulties, particularly, in case of unsteady maneuvering characterized by intensive change of kinematical parameters (linear and angular velocities and accelerations) as well as of angles of attack and slip angle within wide ranges.
In this connection let use a universal mathematical model [3] based on the integral model of the main rotor that provides adequate accuracy of its total aerodynamic characteristics. The influence of the airframe on aerodynamic characteristics of the main rotors is neglected. Besides, we use the hypothesis of stationarity and hypothesis of flat sections. All elements of the helicopter and UA are assumed to be absolutely rigid.
Taking into account insignificant change of induced velocities along the span of the UA wing let consider only its longitudinal motion.

Considered is UA of aircraft type in a classic configuration with constant stabilizer-setting angle. The stabilizer is situated in the jet of the propeller delivering thrust of 25kg.
At the first stage computations of the trim of the helicopter with a strictly fixed UA are carried out up to the moment of launch.
Trim equations are as follows:

$$\dot{V}_{KXSYS} = X_{SYS} / m_{SYS} = 0, \quad \dot{V}_{KYSYS} = Y_{SYS} / m_{SYS} = 0, \quad \dot{\omega}_{ZSYS} = M_{ZSYS} / I_{ZSYS} = 0.$$

where:

$$X_{SYS} = \sum_{i=1}^{2} X_{MRi} + X_{AFH} + X_{PROP} + X_{AFAC},$$

$$Y_{SYS} = \sum_{i=1}^{2} Y_{MRi} + Y_{AFH} + Y_{AFAC},$$

$$M_{ZSYS} = \sum_{i=1}^{2} M_{ZMRi} + M_{ZAFH} + M_{ZAFAC}$$

As a result of computations the pitch angle of the system and the position of the main rotor collective pitch and longitudinal deflection of the swashplate are defined. These parameters are initial conditions for the second stage of computations - determination of longitudinal disturbed motion of UA.
Here it is assumed that the helicopter after launching the UA remains in trim mode, i.e. initial conditions are kept: H=const, V=const, ω=0.
At the same time UA performs longitudinal disturbed motion according to equations:

$$\dot{V}_{KXAC} = X_{AC} / m_{AC}, \quad \dot{V}_{KYAC} = Y_{AC} / m_{AC}, \quad \dot{\omega}_{ZAC} = M_{ZAC} / I_{ZAC}.$$

where:

$$X_{AC} = X_{AFAC} + X_{PROP} + X_{DIST} - mg \sin\vartheta + m\ \omega_Z V_{KY},$$

$$Y_{AC} = Y_{AFAC} + Y_{DIST} - mg \cos\gamma \cos\vartheta - m\omega_z V_{кх}, \qquad M_{ZAC} = M_{ZAFAC} + M_{ZDIST}.$$

$$X_{AFAC} = X_F + X_W + X_{FIN} + X_{STAB}, \quad Y_{AFAC} = Y_F + Y_W + Y_{STAB}, \quad M_{ZAFAC} = M_{ZF} + M_{ZW} + M_{ZSTAB}.$$

It should be noted that kinematical equations of the coupling between angles and angular velocities of pitch are solved for a general case of motion that has no singular points [4]. This makes it possible to derive helicopters motion with any change of angles which is important in studying the aircraft maneuvering in space.

Results of maneuvering and its analysis

Different variants of launching unmanned aircraft (without autopilot) have been considered:
1- direct launch from the beam holder;
2- launch from the starting rod with the length of 1.7m.;
3- launch from the starting rod with a booster delivering thrust of 25kg during two seconds.

The results of launch computations are given in Figures 10-12. The upper plot shows relative (about a starting point on the wing) aircraft motion (m) in the longitudinal plane as well as the position of the blade at the azimuth of 180°. The lower plot shows the change of the pitch angle in degrees and vertical speed of the unmanned aircraft (m/s) depending on time of its flight.

Let analyze the results derived and compare different variants.
After launching (variant 1) at speed of 50km/h (Fig.10) the aircraft begins intensive decent with abrupt change of the pitch angle. In this case the horizontal speed increases (in 3.5 seconds of flight the decent is about 70m, while relative longitudinal displacement reaches 13.5m) because the wing and tail are in the intensive flow generated by the main rotor and do not produce the lift. With further increase of the launching speed, the situation becomes better: the aircraft more intensively develops the speed of horizontal flight and reduces decent speed as the wing and tail begin operating. For example, at launching speed of 125km/h the aircraft accelerates to the speed of 160km/h in 3.5s, the speed of vertical decent increases to -2m/s, the settling from the moment of launch is 9m, relative longitudinal displacement reaches 20m.

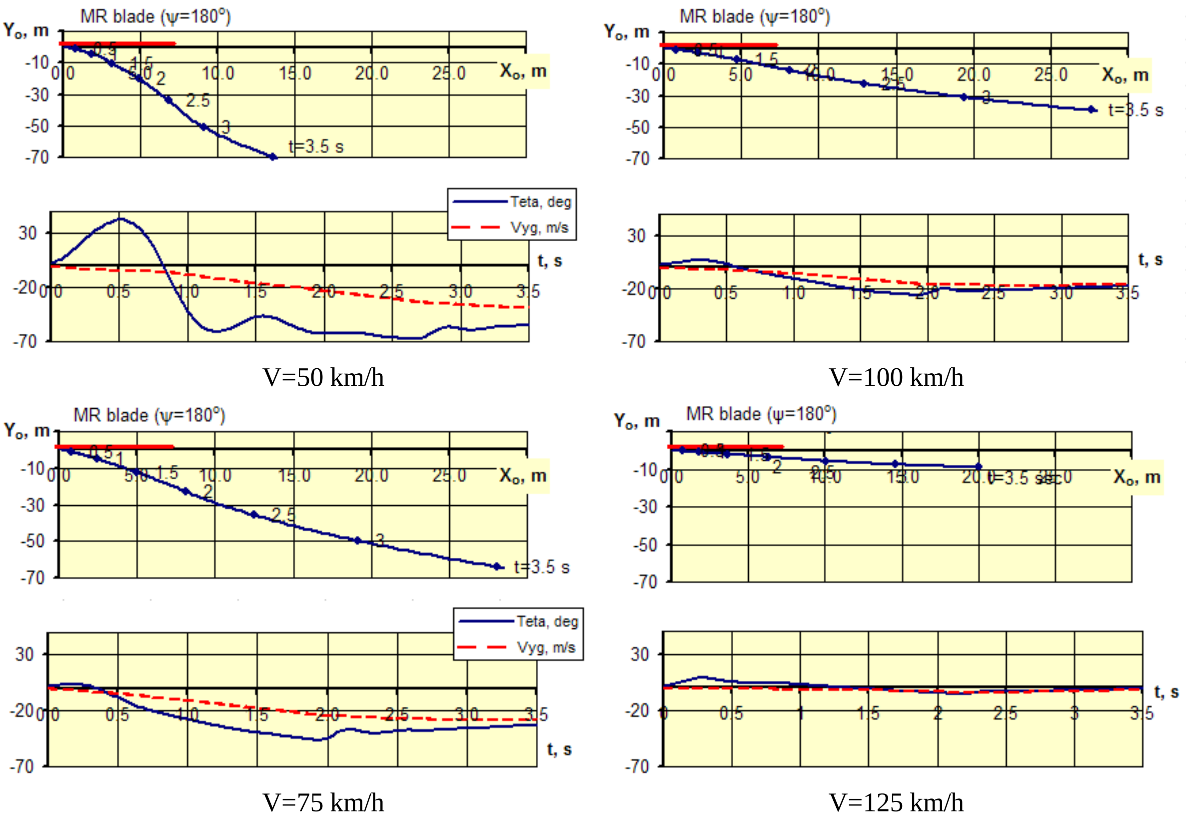


Figure 10: UA launch (variant 1, H=100 m, ISA)

The comparison of launch variant 2 with variant 1 reveals that the aircraft launch from the rod at speeds of 50 and 125km/h improves the results: decent speed and amplitude of longitudinal oscillations reduce, while relative longitudinal displacement increases (Fig.11).
In case when the aircraft is launched from the rod with booster (launch variant 3) the results are more favorable (Fig.12).
With launching speed of 50km/h the rod and booster provide an adequate value of decent (which is close to the analogous value when launching without the rod and booster at speed of 125km/h), less pitch oscillations and larger longitudinal displacement. The use of the rod and booster at speed of 125 km/h improves the characteristics of the aircraft motion too.

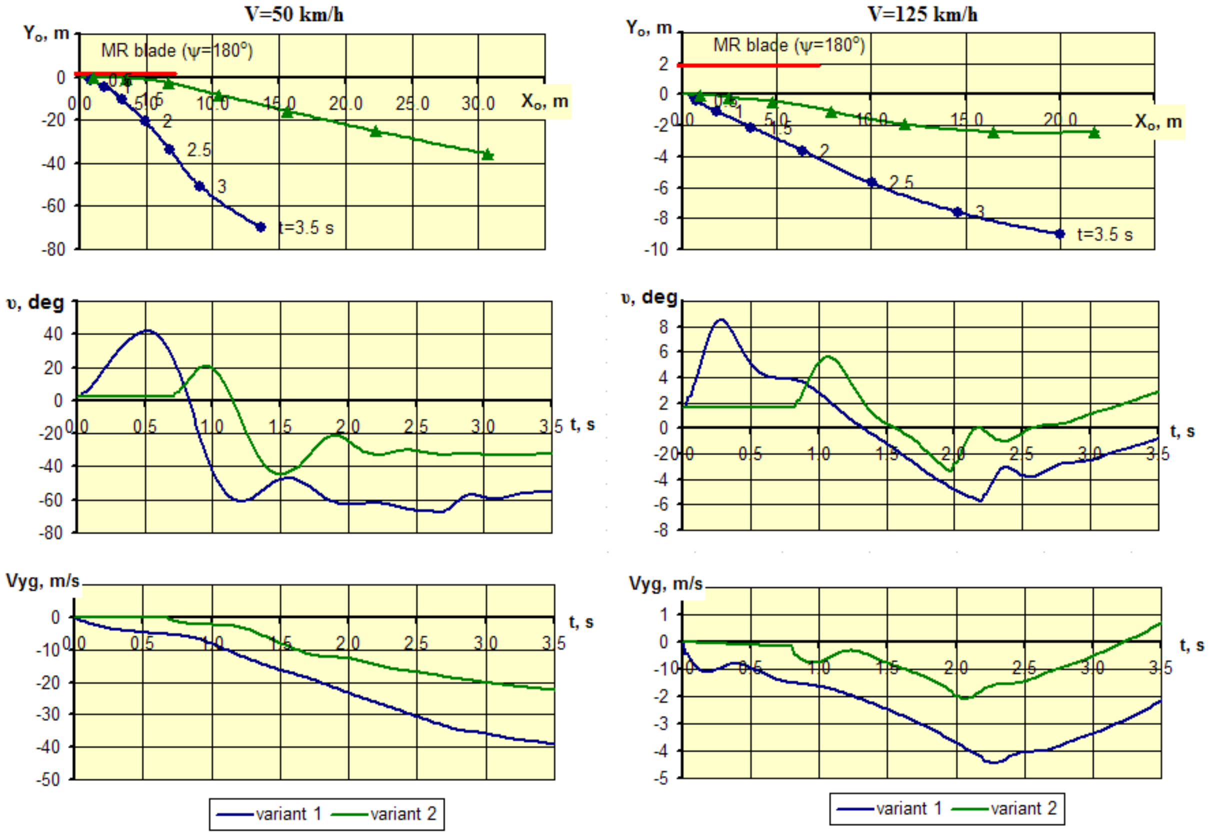


Figure 11: Comparison of launch variants 1and 2

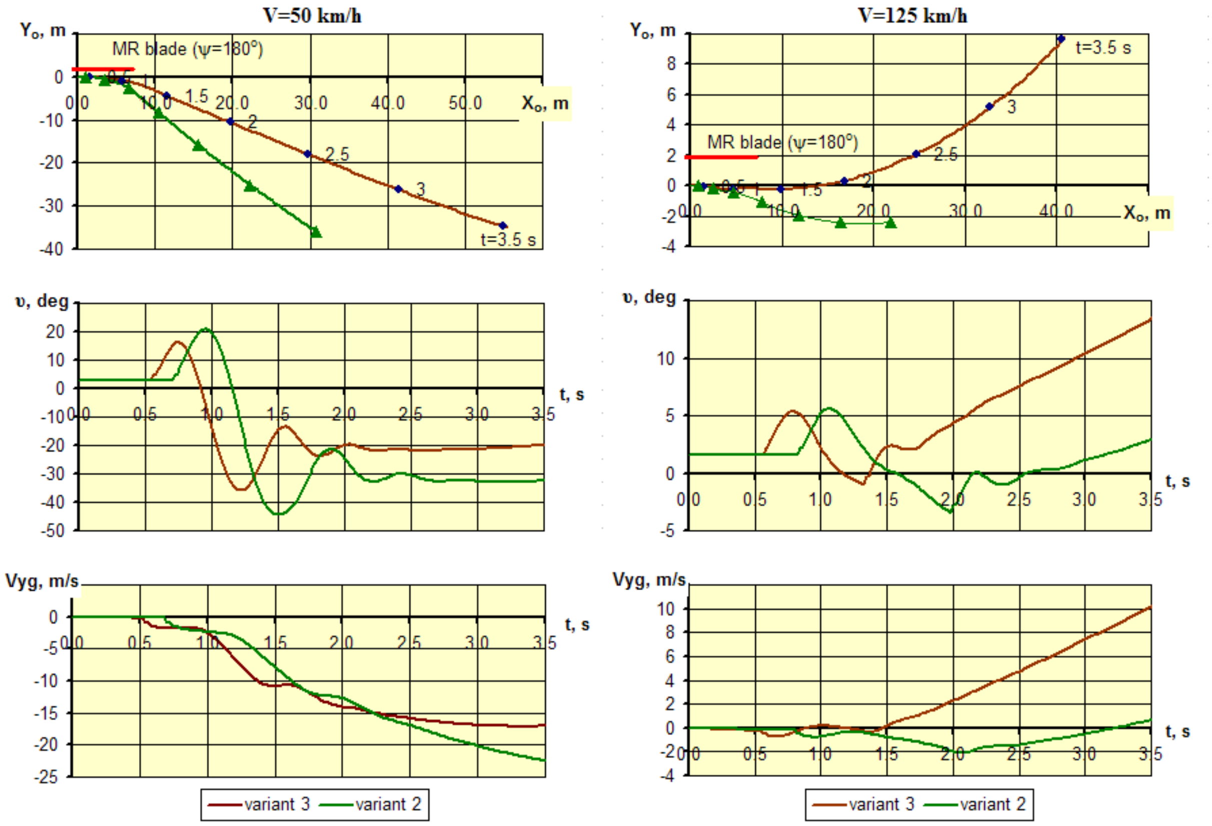


Figure 12: Comparison of launch variants 2and 3

CONCLUSIONS

The preliminary studies carried out by the authors confirm the possibility of launching a low-speed unmanned aircraft from a helicopter within a range of flight speeds more than 50km/h. A dangerous closing between the aircraft and helicopter does not take place. The pattern of the aircraft motion can be significantly improved by using the rod and booster.

REFERENCES

[1] V.A. Anikin *"Rotor Disc Vortex Theory and It's Application in Helicopter Aerodynamics"*, - Trudy of the Second Scientific Reading Dedicated to B.N. Yuriev's memory. Moscow, March 1987, IIE AN USSR, M., 1988

[2] Anikin V., Kritsky B. *Multilevel Mathematical Model of Rotorcraft Aerodynamics*. 27th European Rotorcraft Forum. September 11-14, 2001. Moscow.

[3] V.A. Leontiev, V.A. Anikin. *Nonlinear mathematical model of helicopter motion*. 58th AHS Annual Forum. June 11-13, 2002. Montreal, Canada.

[4] A.A. Shilov. *General Equations of Aircraft Motion Without Singular Points*. Trudy TsAGI, issue № 850, 1962.