SOLUTION OF HELICOPTER FLIGHT DYNAMIC TASK BY OPTIMAL CONTROL THEORY MEETHODS

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Solution of helicopter flight dynamic tasks by methods of the modern control theory and optimal control theory in particular is considerably more complicated than solution of the same task for fixed wing aircraft. This can be explained by a more complicated model of a helicopter flight, larger number of limitations and non-linearities. Recent developments in the field of specific approximated methods of optimal control theory and flight dynamic models made it possible to solve helicopter flight dynamic tasks.

That became possible because of three provisions:

- development of science on stability, controllability and maneuverability of rotorcraft, development of flight dynamic models taking into account all helicopter peculiarities as a control object [1], [2], [6], [7], [8];
- development of applied methods of optimal control theory with the aim to solve tasks with non-linear control objects and control consecutive amelioration methods [2], [4], [5], [9], [10], [11];
- improvement of computing equipment allowing to perform complex calculations in comparatively small time periods;

By present time, optimal control theory methods have allowed to solve a large enough scope of tasks (fig. 1) including the following:

- identification of non-linear mathematical models of helicopter motion based on series of experiments (ground and flight tests);
- optimization of helicopter flight trajectories both spatial and low altitude;
- optimization of helicopter flight control in specific flight conditions including various failures. For piloted helicopters this control is implemented by an autopilot and as a directive control in order to reduce the pilot workload and automatic control is implemented for a unmanned helicopters.

1. Development of helicopter motion mathematical models

Development of a control object model is of paramount importance for control optimization task solution. It is most important here that inclusion of too many factors insignificant for the given conditions leads to complication of the model and a failure to include the required factor can make the obtained solution practically zero. Experience of solving practical flight dynamic tasks allowed to develop a hierarchy system of models considerably differing in complexity, i.e. by state phase dimensionality, by control vector dimensionality, by initial equation system degree of non-linearity (fig. 2). Practically all these models were used to solve helicopter control optimization tasks in various conditions [15], [14], [17], [18].

Experience of solving optimization tasks by control consecutive amelioration method demonstrates that besides a good model, a realization of multiple limitations existing at real helicopter is very important for solution of such tasks. A large number of limitations existing on the helicopter required development of a special algorithm of penalty function coefficients control [12].

2. Identification of motion models

Identification of an object mathematical model is one of two flight dynamic task components upon which depends solution of the other task component — control optimization. The main difficulty in identification of the helicopter motion model is connected with the model non-linearity and the fact that test results, especially flight test results, contain occasional errors and can be incorrect or influenced by hazardous factors. Based on the optimal control theory methods, a method of non-linear motion model identification was developed using results of a series of experiments [13]. Analysis of the motion parameter variation dependencies allows to define the main parameters that mainly make identification a success. Thus, when optimizing control in conditions of zooming, variations of flying speed, pitch angle and main rotor speed were selected as the main parameters. In the result of identification based on a series of experiments [13], the motion model is more consistent with the experiment results and which is more important, the results of a series of experiments.

3. Flight trajectory optimization

3.1. Point-to-point flight trajectory optimization.

Definition of optimal trajectory of a helicopter point-to-point flight, that is especially important for a unmanned helicopter, establishes control ensuring an optimal flight trajectory including all limitations that are important for such limitation conditions (available power, control system characteristics, limitations of helicopter speed and attitude) [17].

3.2. Low-altitude flight trajectory optimization

Optimal low-altitude flight trajectory is built on the basis of a digital map of the terrain over which the helicopter flies. A special method [14] is developed based on control consecutive amelioration that allows to take into account the main helicopter limitations, i.e. available power, available vertical speed etc. Here the main difference between fixed wing and rotary wing task lies in the necessity to consider the dependence of available vertical speed upon translation at flight speed. The developed methodology [14] allows not only to define helicopter low altitude flight trajectories but also investigate the influence of various factors, i.e. pressure altitude (fig. 3), available power, wind etc. upon his trajectory.

4. Flight conditions automation

4.1. Automation of standard maneuvers

The general helicopter mission flight trajectory can be divided into certain components (fig. 4) — climb, turn, acceleration, deceleration, routed flight etc. Such standard maneuvers as climb, acceleration, deceleration, directional turns, zooms, dives, flat and 3D maneuvers can be selected as objects for automation of flight along certain trajectory. Fig. 5 presents a control optimization task solution for combat 3D maneuver of a combat turn type.

4.2. Automation of landing at one engine failure

Definition of optimal control at failure of for example, engine has been performed for two modes — horizontal flight in low altitude flight and autorotation landing when there is enough altitude to enter autorotation at the moment of one engine failure. A large scope of calculations performed to optimize landing from autorotation allowed to evaluate influence of various design parameters (helicopter weight, limited pitch angle at landing, allowed limitations of vertical speed). Solution of a task of one engine failure at how altitude (fig. 6) allows to find a safe H-V (“hight-velocity”) zone. In this zone, obtained by solution of a Ka-26 helicopter control optimization task for one engine failure at low altitude, a flight test point is marked that correlates well with the analytical zone.

Conclusions

1. Optimal theory methods allow to solve a wide range of helicopter flight dynamic tasks including:

- definition of optimal path, both spatial and for low altitude flight;
- automation of individual flight models and the flight in general;

- automation of helicopter control in failure conditions, like engine failure conditions.

2. In the process of solving practical tasks Kamov Company has accumulated broad experience in formation and solution of helicopter flight dynamic tasks, including:

- development of a hierarchy system for the helicopter flight dynamic models;
- techniques enabling to account for numerous rotorcraft limitations and nonlinearities;
- practical optimization methods for individual maneuvers aimed at reduction of pilot load in automated flight of remotely piloted rotorcraft.

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System of Helicopter Motion Models

Table 1

	Full linear	Partly linear	Linearized (only longitudinal or only lateral)	Linearized 3D	Non-linear (only longitudinal or only lateral)	Non-linear 3D
Order of motion system	3	3	7	14	7	14
Dimension of control vector	1	1	2	4	2	4
Degree of linearization	Linear equations with constant coefficients	Linear equations with constant coefficients, 1-2 limits	Partly linearized with basic non-linearities and limits		Non-linear characteristics of aircraft (α= -180…+180 deg., β =-180…+180 deg) and of main rotor	
Number of limits: current final	 6 1	 4 2	 Up to 10 4	 Up to 20 10	 Up to 10 4	 Up to 20 10
Derivation method	analytical				numerical	
Examples of tasks solution	Design parameter influence	Vertical modes automation	Automation of modes in vertical plane	Automation of 3D modes	Automation of modes in vertical plane	Automation of 3D modes

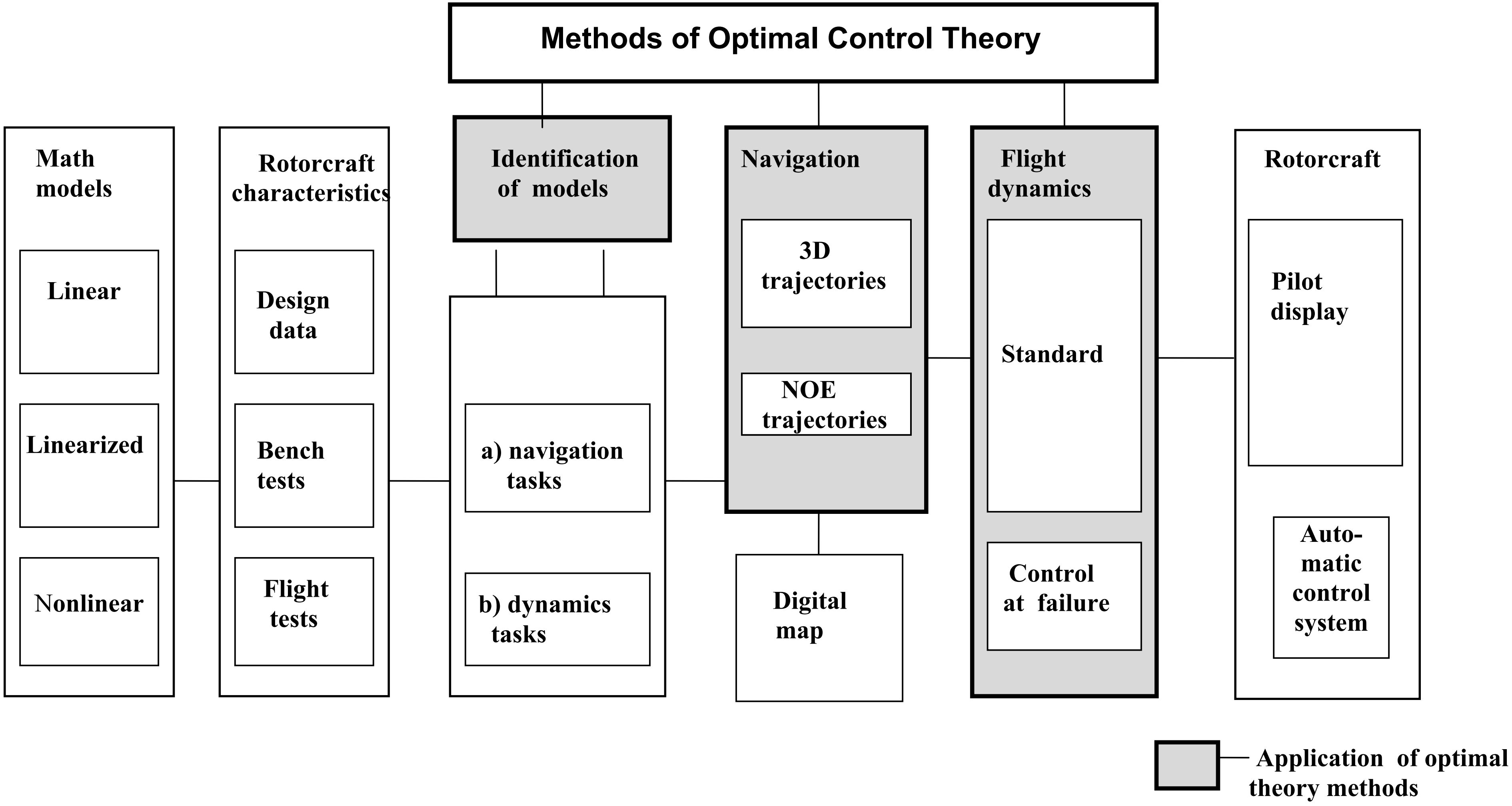


Fig. 1 Application of Optimal Theory Methods in Helicopter Dynamics Tasks

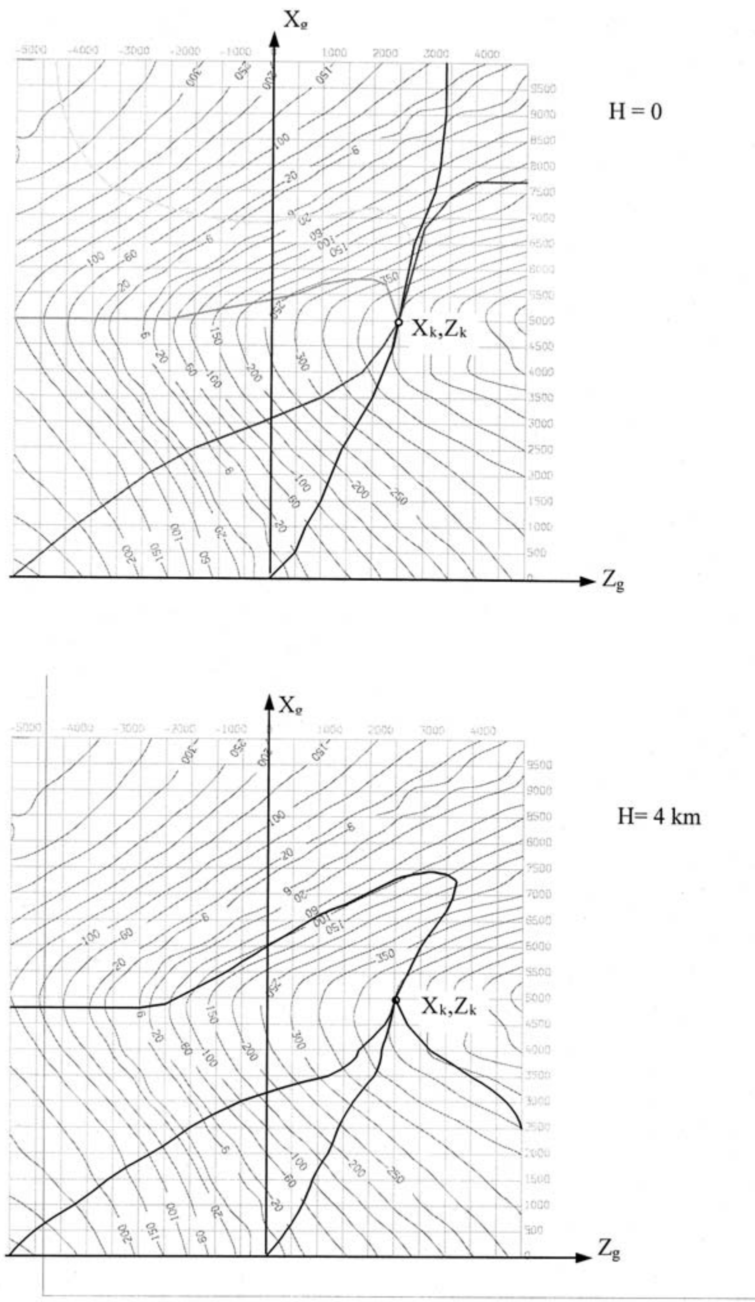
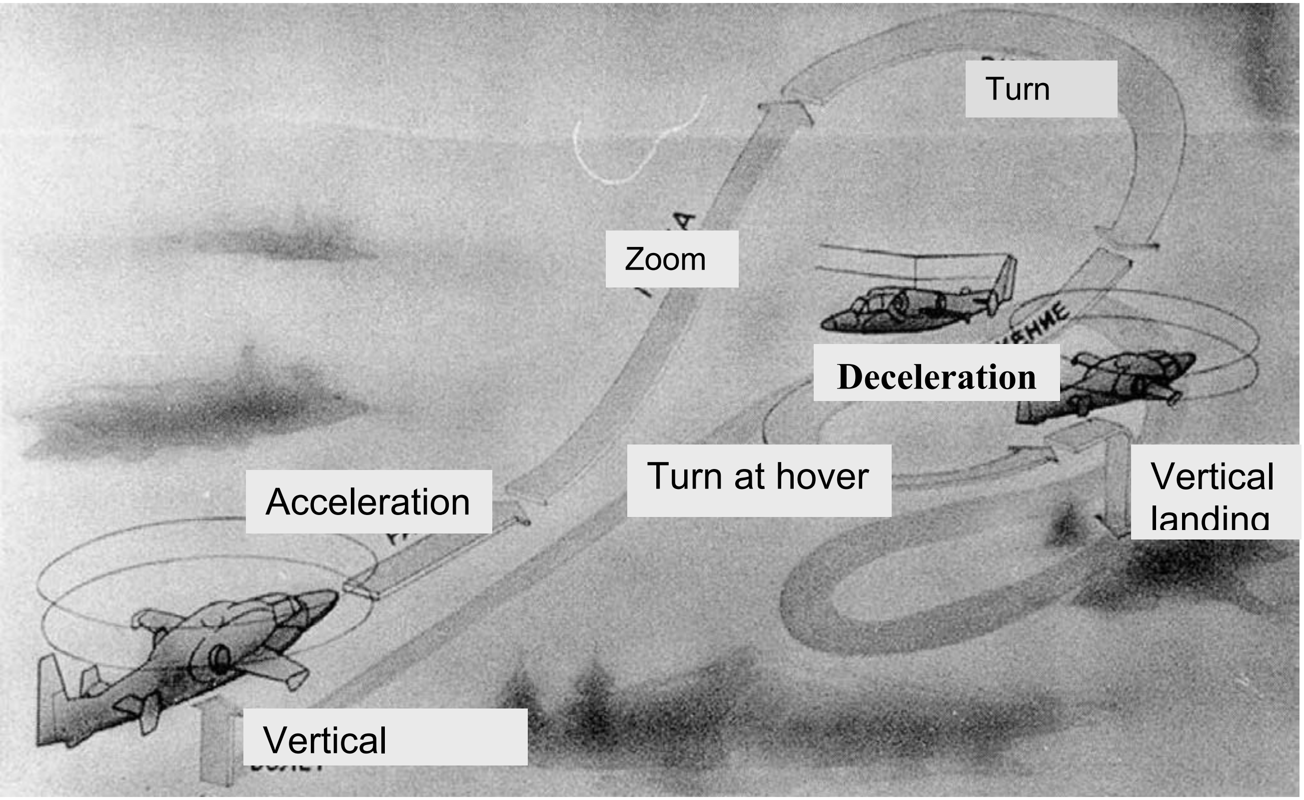


Fig. 2 NOE trajectories to final point (Xk,Zk) from different initial points

Fig. 3 Automation of basic maneuvers and modes



Standard maneuvers

1. **Level plane**
   - acceleration/ deceleration
   - turn on 90 degrees
   - turn on target
   - bringing in turn
   - flat turn

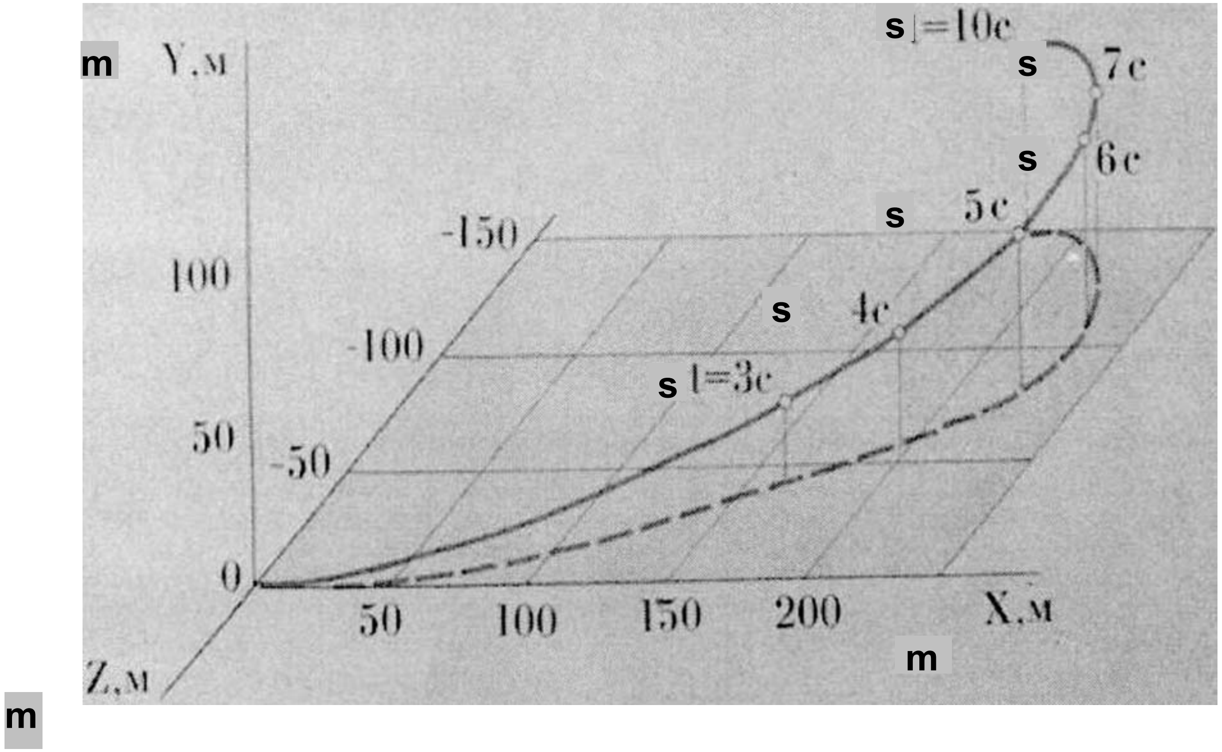
2. **Vertical plane**
   - vertical take off
   - vertical landing
   - diving
   - climb

Safety at failure

- autorotation landing
- landing after engine failure at low height
- parametric investigation of landing characteristics after engine failure
- determination of “H-V” zone

3. **3 D**
   - turn with climb
   - climbing turn
   - approach to hover

Fig. 4 Turn with climbing



State vector:

$\{Vx, Vy, Vz, \omega x, \omega y, \omega z, Mk_{дв}, X, Y, Z\}$

Control vector

$\{\delta z, \delta x, \varphi, \Delta\varphi дош\}$

Current limits

$Vx \geq Vx_{min}$, $|\delta z| \leq \delta z_{max}$;

$\vartheta \leq \vartheta_{max}$, $|\delta z| \leq \delta z$;

$|\gamma| \leq \gamma_{max}$, $\varphi_{min} \leq \varphi \leq \varphi_{max}$;

$\omega \leq \omega доп$, $|\Delta\varphi дош| \leq \Delta\varphi дош_{max}$

Final limits

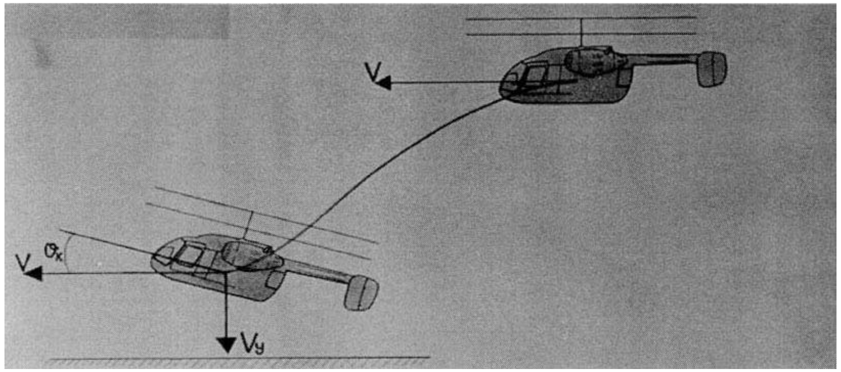
$\Delta\psi$ (tk) = π;

ΔH (h) = max;

ΔH (h) = 0;

$\Delta\vartheta$ ($\Delta\gamma$) = 0

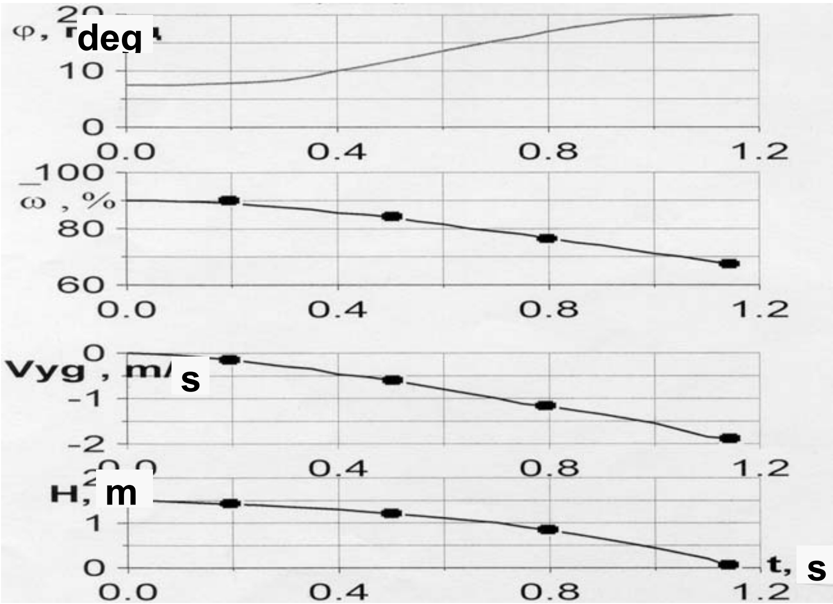
Fig. 5 Landing after engine failure at low height



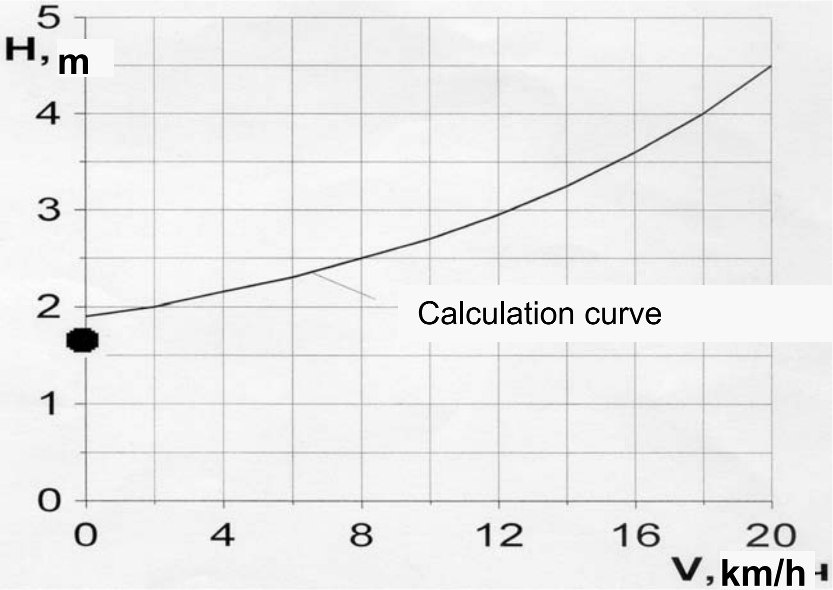
Basic limits:

- descent rate $Vy_g\,(tk) \geq -2.5$ m/s;
- descent speed Vk ≤ 15 кm/h;
- pitch angle υk ≤ 12˚;
- RPM ω̄k ≥ 60%

Comparison with flight test



Safety zone



Calculation curve

● – Flight test point