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# NAP-OF-THE-EARTH FLIGHT OPTIMIZATION USING OPTIMAL CONTROL TECHNIQUES

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## Abstract

Nap-of-the-Earth task solutions with the application of the optimal control theory and dynamic programming are discussed here. In particular, a problem of an optimal flight path definition from the digital map data is solved using a dynamic programming technique.

A piloting/navigational equipment package configuration is defined for the needs of a helicopter nap-of-the-earth flight by using capability offered by optimal control techniques in automation of certain maneuvers.

## 1 Introduction

The amount of publications devoted to the nap-of-the-earth ( NOE ) flight problems has grown up recently both in Russia and abroad [1], [8].....[14]. These problems are treated from all points of view i.e. helicopter maneuverability, flight condition and maneuver automation, control system configuration etc.

Summarizing the main approaches to NOE flight investigations the following of them may be mentioned as most important:

- evaluation of extremely low altitude NOE flight special importance for modern helicopter;
- investigations in the field of developing an automatic guidance and preset flight path generation structure ( based on the terrain digital map data );
- development of an advanced control system including automatic control system maximally facilitating flight in the immediate proximity of ground surface for the pilot, automation of certain flight modes and maneuvers;
- selection of sensors providing for NOE flight.

Adoption of optimal control theory and dynamic programming for treatment of those problems shall be discussed below.

## 2 Setting of a problem

The main NOE problems that may be solved by optimal control theory and dynamic programming techniques are:

- definition of optimal flight trajectory ( laying out the route ) on the basis of terrain digital map data by methods of dynamic programming;
- automatic performance of certain maneuvers in the course of flight along the preset route by methods of optimal control theory.

Optimization of control in various maneuvers is done by one of optimal control approximation methods developed in 1960-ties by V.F.Krotov [2] on the basis of L.S. Pontriagin theory that found wide application for solution of practical tasks involving large amount of nonlinearities and restrictions.

A report was delivered at one of preceding European Forums [6] that was devoted to presenting the method in detail as well as to peculiarities of its application and results obtained. So the following discussion will concentrate only on optimal flight trajectory definition using the terrain map data.

As a multistep optimization task the flight trajectory optimization includes all specific features characteristic for dynamic programming tasks [3] i.e.:

- condition of the system examined is defined by X vector at each step. Further change of condition depends only upon this very condition and does not depend upon how the system has reached that condition;
- at each step one solution is selected under the effect of which the system turns from the proceding $X_i$ to a new $X_{i+1}$ condition;
- at each step the action is connected with a certain gain that depends upon a condition existing at the beginning of a step and upon an adopted control solution;
- restrictions are imposed on condition and control vectors in combination creating an allowable solutions domain;
- it is required to find control for each step that allows to obtain a target function extreme value for the whole integration period ( all steps).

A terrain digital map presented at fig.1 was accepted as an essential condition of the problem solution.

The solution algorithm includes the following main stages (ref. fig 1);

- specifying initial and final helicopter attitudes;
- definition of target function ( path, flight altitude and time minimums etc);
- setting of restrictions (from the point of view of design, energy ) and their implementation;
- evaluation of functional at the end of each interval of specified length when it turns to various angles within the range specified;
- transfer to the next section with initial coordinates corresponding to the functional minimum in the preceding section.

The target function (functional) is determined by various requirements to flight trajectory but the most simple expression taking account of the path and altitude minimum requirements seems to be:

$$I= K_1 * \int_{t_o}^{t_k} Vy\, dt + K_2 * \int_{t_o}^{t_k} Vxz\, dt, \quad K_1, K_2 \text{ - weight rations;}$$

$K_1=0$ - requirement on the flight path minimum only;
$K_2=0$ - requirement on the altitude minimum only;
$V_y$ - vertical speed in the ground coordinate system;
$V_{xz}$ - horizontal plane speed component.

## 3 Main Restrictions

Flight optimization problem solving based on the digital map data does not present much difficulty by itself. The main awkwardness is same as common for a control optimization task, i.e. presence of design and energy restrictions typical for the helicopter.

When defining the trajectory the main restricting factors will be:

- overload ny defining a radius of trajectory curvature when transferring from horizontal flight to linear flight inclined to the horizon ( section A in fig. 2 );
- an $Q_{tr}$ trajectory inclination angle in respect to the horizon defining a trajectory linear section (section B in fig. 2);
- maximal roll angle determining the helicopter capabilities in a horizontal plane maneuver.

The allowed vertical overload as well as the maximal roll angle value are quite well known parameters and are not specified only for NOE flight conditions.

A permissive trajectory inclination angle $Q_{tr}$ is restricted by various factors the most important of them being the power available. This inclination angle is limited by values corresponding to the flight at maximal power and conditions of autorotation ( fig.2 ).

When flying in conditions of the flight geometric altitude stabilization (i.e. in the absence of inclined range indicator warning of an obstacle lying in front) the altitude will always be somewhat lost in the course of bypassing the obstacle $\Delta H$ (fig. 2 ). Taking its permissible value we may define the maximally possible trajectory inclination angle as a function of flying speed and control travel available ( fig.3). In any case if such technique of bypassing the obstacle ( by geometric altitude) is used a trade-off is required to be made between low permissible trajectory inclination angles and high altitude losses in the process of bypassing the obstacle.

The possibilities of bypassing are considerably increased when using inclined range indicator signals. As demonstrated by investigations made [4] if without an inclined range indicator at a specified 5 m altitude loss when bypassing a terrain relief feature, the maximal terrain feature bypass angles are:

- with an autopilot only(20% control) $Q_{max} = 5^{\circ}$,
- with an 100%-control available $Q_{max} = 13^{\circ}$,

then the similar values in the presence of inclined range indicator are correspondingly $8^{\circ}$ and $13^{\circ}$ with the altitude loss being zero. It must be kept in mind that these figures are comparative only and do not take account of sensor, computer etc. characteristics.

Having obtained information on the terrain lying before the helicopter from the inclined range indicator, the helicopter may start the maneuver earlier by the section of path equal to D (fig.3 ) without any altitude loss.

## 4 Definition of the optimal trajectory

Solution of the optimal flight trajectory definition task is done by a dynamic programming technique as described above on the basis of the terrain digital map, presented in fig.1.

An example of a task solution with consideration of a path minimum and limitation of the trajectory inclination angle by various values,i.e. 3, 6 and 8 degrees is shown in fig.5. Fig.5 presents a certain trajectory in a horizontal plane, variation of altitude and the path covered.

Based on the NOE flight automation requirements and taking into account optimal control theory algorithms for standard maneuver ( zooms, dives, turns to a preset angle, decelerations etc.) automated performance defined earlier in [5], [6] it is possible to finally select the elements of a piloting/navigational equipment package required to perform NOE flight. These elements are presented in a block-diagram in fig.6. Besides standard sensors providing for attitude and geometric altitude stabilization, the piloting / navigational equipment package includes the following:

- inclined range sensor;
- permissible flight parameters computer;
- recommended standard maneuvers computer;
- computer of directive control signals and signals for one-time command display of the pilot data display system.

Permissible flight parameters computer defines the maximal helicopter capabilities in vertical maneuvering and permissible overloads, roll angles, permissible trajectory inclination angles, depending upon the flight conditions, weight, altitude et. In horizontal maneuvering obtainable obstacle height values $H_{max}$ and its horizontal plane length $Z_{max}$ are defined correspondingly (fig.6).

Recommended maneuvers computer correlates the maximal helicopter capabilities defined above with the terrain relief defined by the inclined range indicator $H_r$ and $Z_r$. Depending upon the correlation between $H_{max}$ and $H_r$, $Z_{max}$ and $Z_r$ a signal is generated to perform a standard horizontal, vertical or spatial maneuver or deceleration.

The generated signal comes both to the automatic control system and to data display system this ensuring combined work of automatic control system and the pilot facilitating the performance of the pilot's duties.

## 5 Conclusion

1 Adoption of optimal control theory techniques to NOE flight automation tasks solution opens more prospects both in the field of optimal flight path definition on the basis of the terrain digital map and in the field of standard maneuver performance automation when flying along a preset trajectory.

2 On the basis of the dynamic programming theory an algorithm was developed to define flight trajectory, optimal for this or that criterion including the current helicopter limitations, on the basis of terrain digital map data.

3 Including the results of previous developments on standard maneuver automation based on optimal control techniques, a configuration of piloting/navigational equipment package was defined that included, besides traditional sensors providing for attitude and geometric flight altitude stabilization, the following additional means:

- inclined range indicator;
- permissible flight parameters computer;
- recommended maneuvers computer;
- directive control and one-time command computer.

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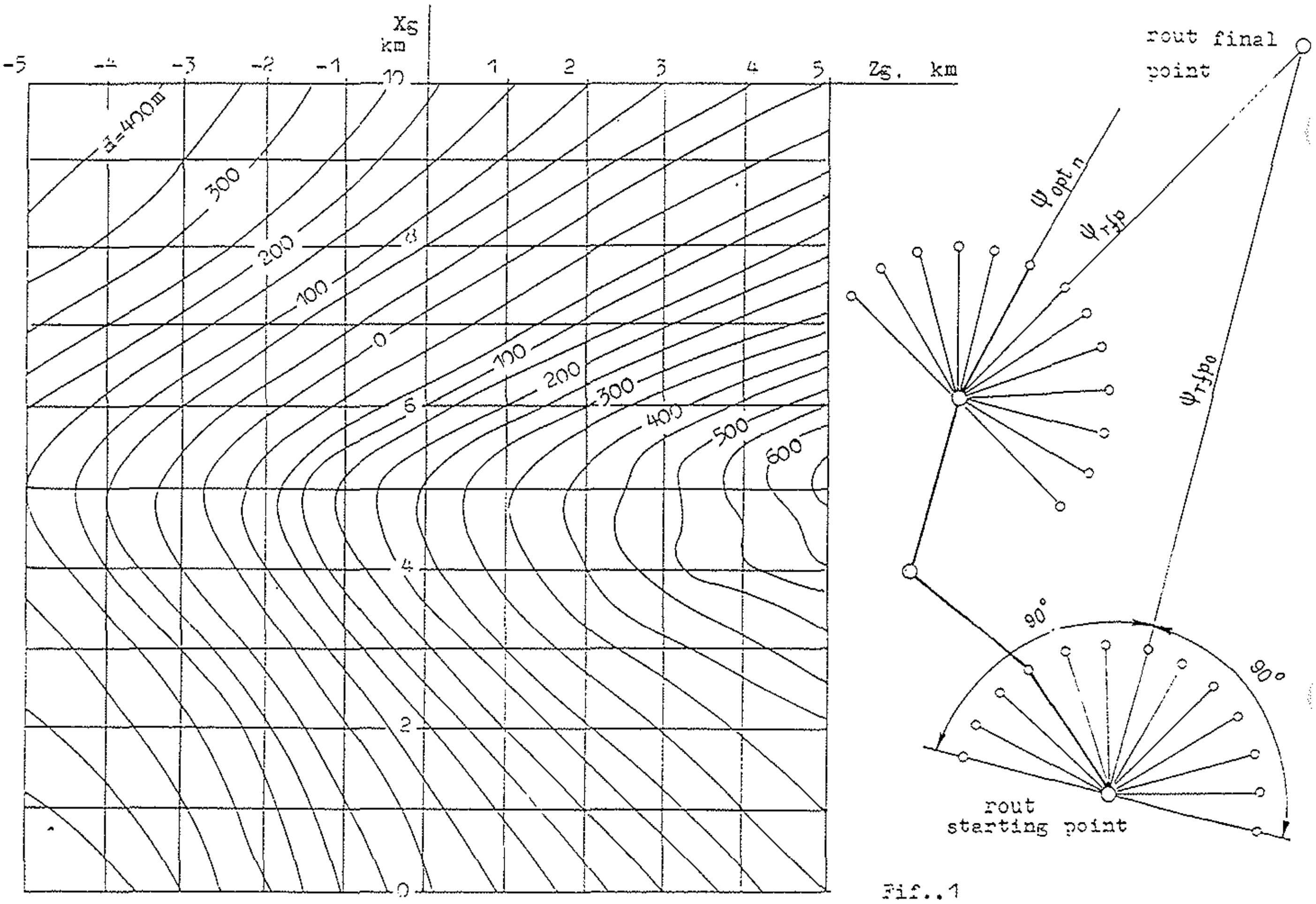
Xg
km
-5
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1
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5
Zg. km
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2
0
H=400m
300
200
100
0
100
200
300
400
500
600
rout final point
$\psi_{opt\,n}$
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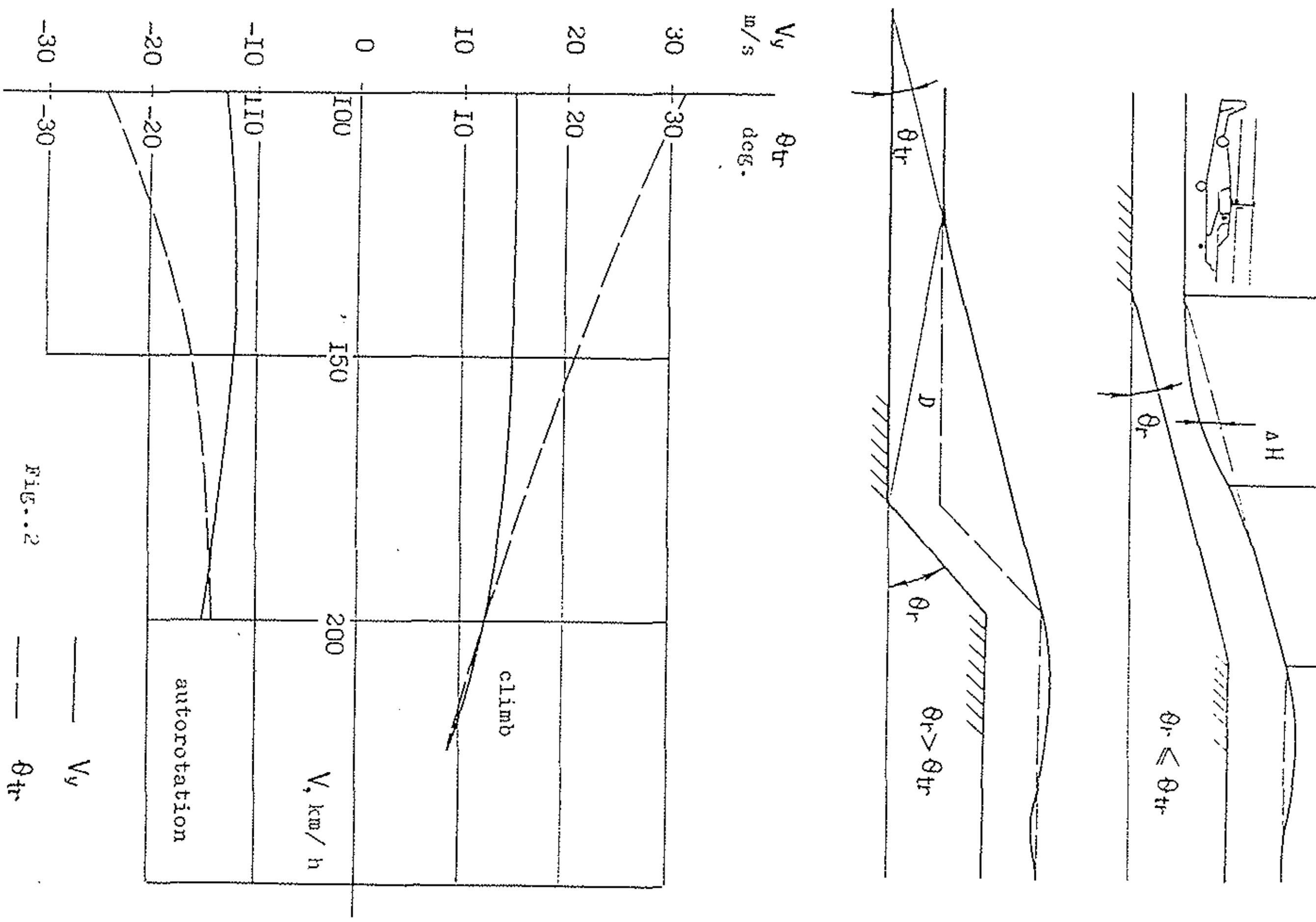
$\psi_{rfp_0}$
90°
90°
rout starting point

Fif..1


$V_y$ m/s
-30
-20
-10
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10
20
30
$\theta_{tr}$ deg.
100
150
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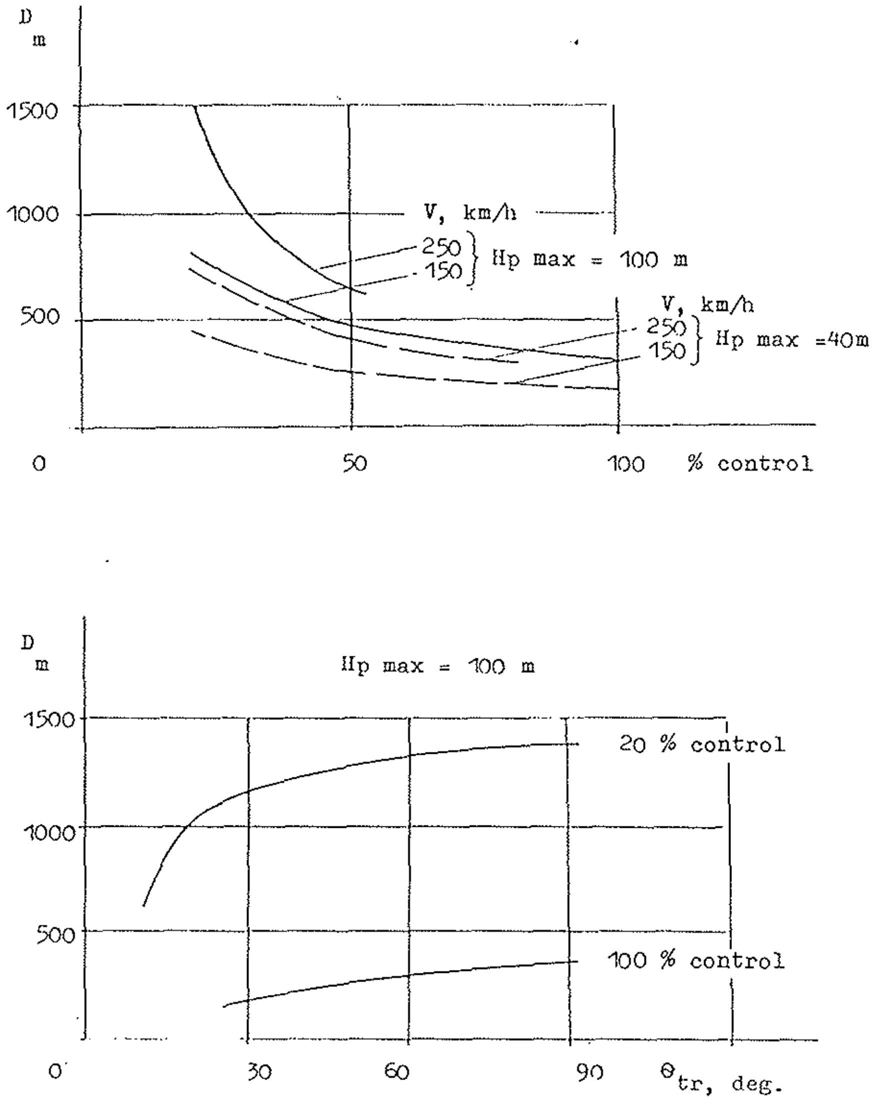
V, km/h
climb
autorotation
$V_y$
$\theta_{tr}$
$\theta_{tr}$
D
$\theta_r$
$\theta_r > \theta_{tr}$
$\theta_r$
ΔH
A
B
$\theta_r \leqslant \theta_{tr}$

Fig..2


D
m
1500
1000
500
0
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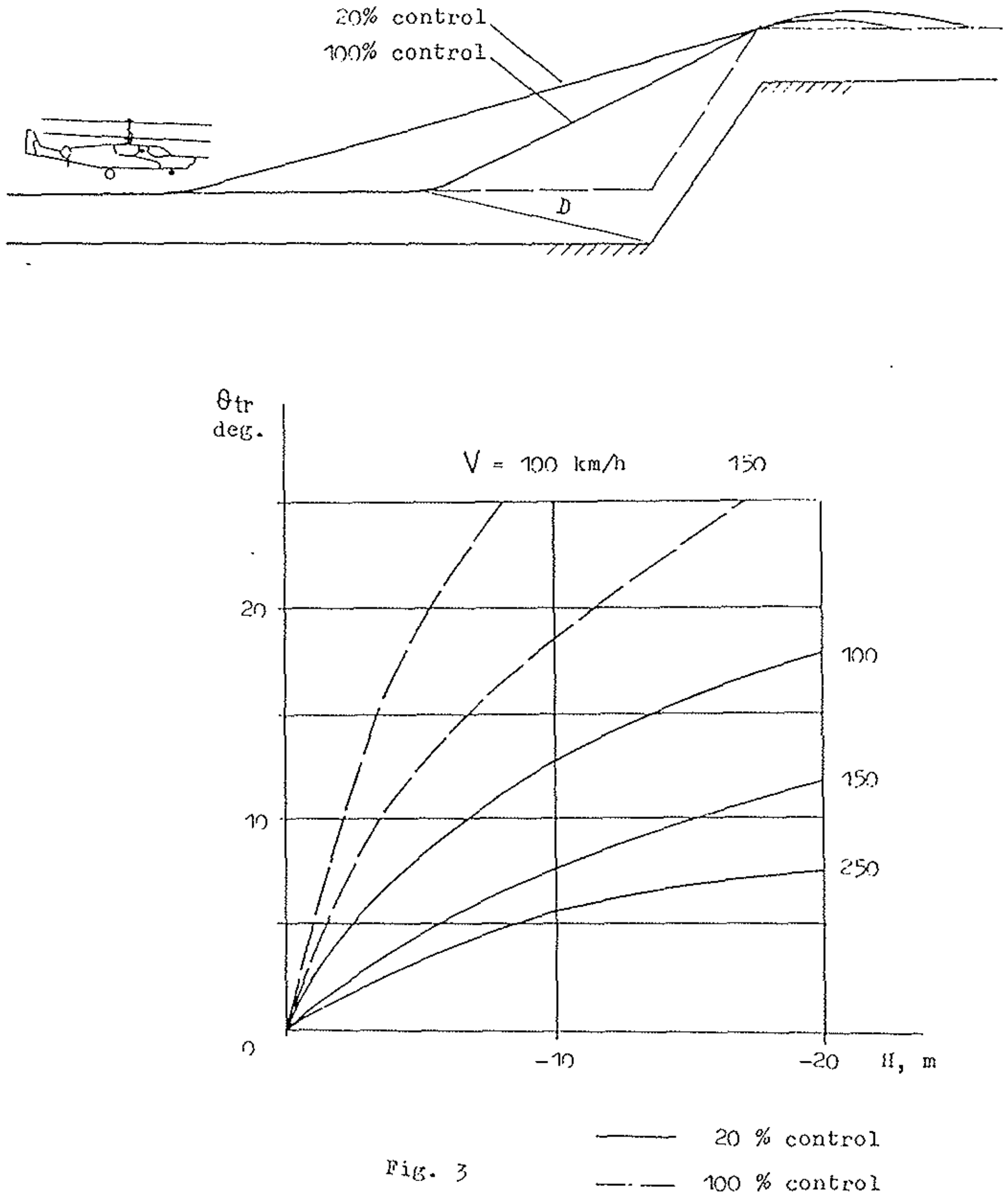
100
% control
V, km/h
250
150
Hp max = 100 m
V, km/h
250
150
Hp max =40m
D
m
Hp max = 100 m
1500
1000
500
0
30
60
90
θtr, deg.
20 % control
100 % control

Fig.. 4


20% control
100% control
D
θtr
deg.
V = 100 km/h
150
20
10
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100
150
250
-10
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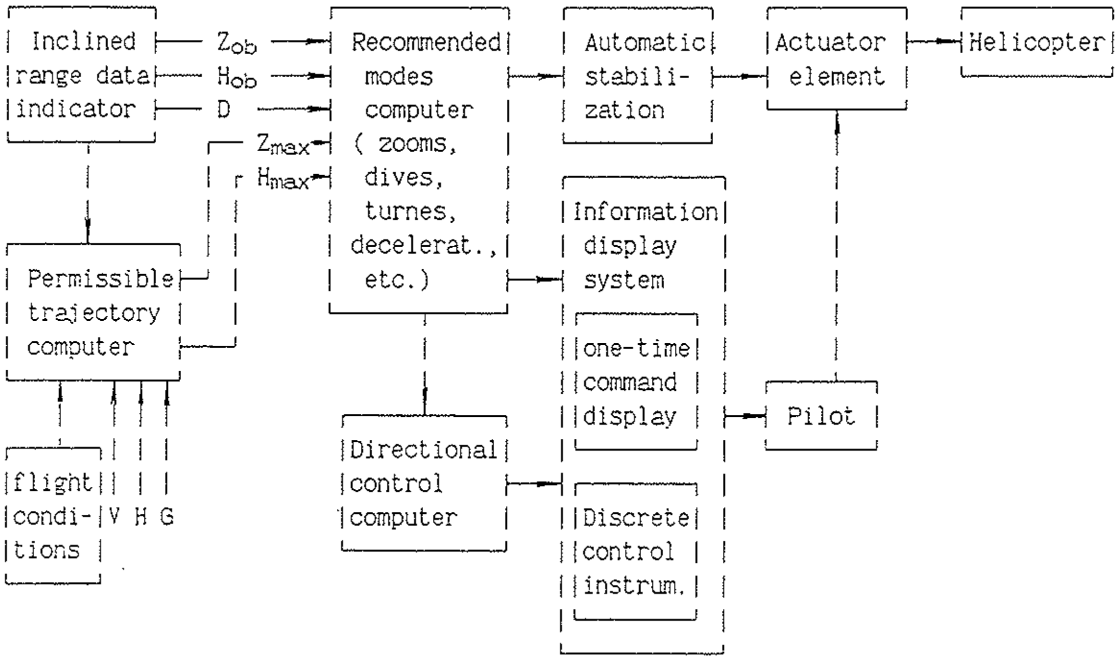
H, m
20 % control
100 % control

Fig. 3


Inclined range data indicator
Zob
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D
Zmax
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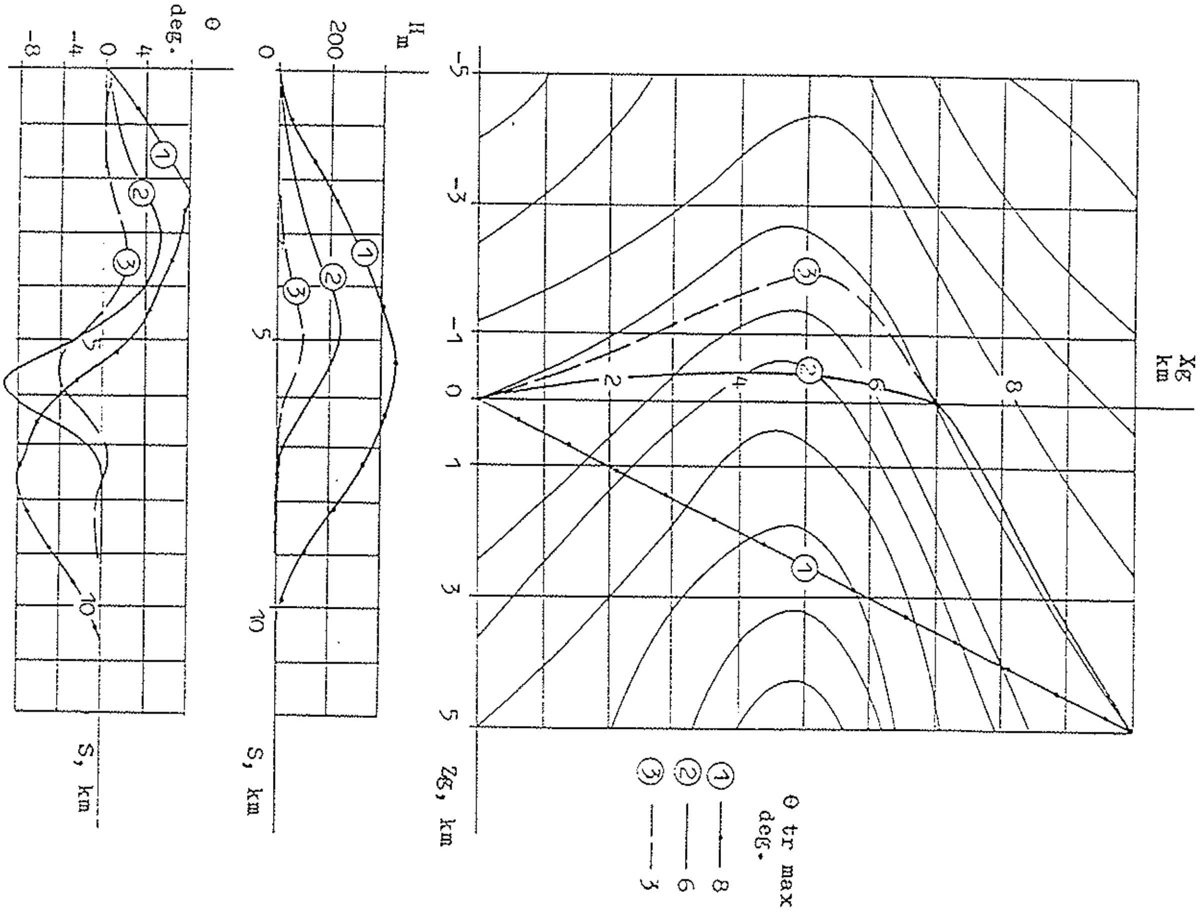
Recommended modes computer ( zooms, dives, turnes, decelerat., etc.)
Automatic stabili-zation
Actuator element
Helicopter
Information display system
one-time command display
Discrete control instrum.
Pilot
Permissible trajectory computer
Directional control computer
flight condi-tions
V
H
G

Fig. 6


θ deg.
-8
-4
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S, km
H m
0
200
5
10
S, km
-5
-3
-1
0
1
3
5
Zg, km
Xg km
2
4
6
8
θ tr max deg.
① 8
② 6
③ 3

Fig. 5