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FLIGHT PATH CALCULATIONS FOR A HELICOPTER IN AUTOROTATIVE LANDING

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Abstract

The capability for helicopters to perform autorotative landings is of great importance, also for the modern ones. In theory the autorotative landing can be carried out safely, when the restrictions of the height-velocity diagram are taken into account. A save autorotative landing requires professional management from the pilot with respect to the energy exchange.

A computer simulation programme has been developed for the calculation of the flight path for a helicopter in autorotative landing. The computation method is based on the energy method where one source of energy can be exchanged for that of other sources. Interviews with helicopters test pilots have provided a review of the practical techniques and procedures to accomplish a safe autorotative landing. These interviews have been determined and translated into usable procedures for a control model.

The autorotative flight can be investigated by variation of the pilot inputs, the pilot cues and the initial and boundary conditions. This model can be used to analyse the most optimal performance of an autorotative landing by manual iterations.

Notations

a	acceleration
D	drag
g	gravity
h	height
I_{fus}	inertia of fuselage
I_{rot}	inertia of main rotor, tail rotor and drive train based on main rotor speed.
m	mass
P	power
q	pitch rate of helicopter
T	thrust
t	time
V	total air speed
W	weight
τ	angle between undisturbed airflow and x-axis
Θ_{pr}	mean blade pitch
Θ	angle between tip path plane and x-axis
Ω	main rotor speed

Subscripts

acc	accessory	q	pitch rate of helicopter
aut	based on steady autorotation	req	required
av	available	T	based on thrust
eng	engine	tr	tail rotor
fus	fuselage	x	in direction of x-axis of the earth axis system
i	induced	z	in direction of z-axis of the earth axis system
kin	kinetic		
mr	main rotor		
pot	potential		

Acronyms

FAA	Federal Aviation Administration
Mil. Std.	Military Standard
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
rpm	revolutions per minute
TPP	Tip Path Plane

1 Introduction

The capability for helicopters to perform autorotative landings is of great importance, also for the modern ones. Because of the complexity of the manoeuvre, the autorotative landing is frequently practised by helicopter pilots. In theory the autorotative landing can be carried out safely, when the restrictions of the height-velocity diagram are taken into account. However in practice the autorotative landing many times have ended with a damaged aircraft or worse.
The basic principle of the autorotative flight is the exchange of energy between the kinetic and potential energy sources of the helicopter. The actuation of the controls depends on the status of the main rotor rotational speed, height, velocity, course and attitude of the helicopter, the so called pilot cues. By applying appropriate control inputs the helicopter pilot manages the required energy exchange.

2 Autorotative Flight

In an autorotative flight a sequence of various flight phases can be distinguished. For the present study the subsequent phases have been considered in detail. The description of the flight phases and the various initial conditions were determined during several interviews with helicopter test pilots of the Royal Netherlands Air Force.

2.1 Initial Conditions

From pilot interviews appears that the velocity and height of the helicopter at the moment of engine failure determine the appropriate initial control actions and the selection of the pilot cues during the following autorotative flight. Combinations of height and velocity, which require different initial control actions, are subdivided in several height velocity areas. These areas are represented in figure 1. For the subdivision in the height-velocity areas it is assumed that the helicopter carries out a symmetrical level flight, because climbing or descending is of influence on the subdivision. In the various height velocity areas, the pilot cues have a different priority in case of an engine failure, e.g. in a low level flight, height has more priority then rotor rpm. The different priorities of the areas of figure 1 are:

- rotor rpm has the first priority for the areas A, B, D and G.
- height has the first priority in area C.
- velocity has the first priority in the areas E and F.
- flying direction has the first priority in area H.

Because of the different priorities in the height-velocity areas, the sequence of the various flight phases will be dependent on the height velocity area the helicopter is flying in. A standard autorotative flight has been defined for which the sequence of flight phases will be discussed in detail.

2.2 Standard Autorotation

A standard autorotation has been defined as an autorotation which is carried out after an engine failure with the helicopter flying at cruise height with cruise speed. In figure 1 this situation occurs in area A. The scheme with the various phases of a standard autorotation is shown in figure 2. Each phase is characterised by four elements: the objective, the control actions, the pilot cues and the result.

Engine failure/reaction time (A)

The helicopter pilot becomes aware of the engine failure by a change in engine noise and a yaw movement of the helicopter fuselage. The yaw movement is usually quickly corrected by a pedal deflection so that the helicopter continuous with the same heading. The main rotor rpm decreases.

First flare (B)

The objective of the first flare is to recover main rotor speed and to reduce the forward speed to the prescribed speed for autorotation. The

autorotation speed is a flight speed between the bucket speed (minimum power required) and the speed where the minimum glide angle occurs.
To reduce the power required, the contribution of the profile power is minimised. Therefor a minimum blade pitch of the main rotor is required.
The first flare can be further subdivided in two parts:

Tilting part: The cyclic stick is pulled aft so that the helicopter fuselage gets a nose up attitude. The angular velocity and the angular acceleration and deceleration during the tilting depends on the decrease of the main rotor rpm. An early recognition of the engine failure by the pilot enables him to prevent a too large rpm drop of the main rotor. In this case a smooth attitude change is sufficient. By tilting the rotor the inflow changes from the upper side to the underside of the rotor disk.

Steady flare: Due to the inflow from the underside of rotor disk and a minimum blade pitch, the rotor rpm increases. The thrust vector points backwards so the forward speed decreases. The helicopter maintain a nose-up attitude until a speed of 5 kts above the speed required for steady autorotation.

Autorotation phase (C)

The objective of the autorotation is to make a controlled descent. During the autorotation the pilot looks for an appropriate landing point. In case the main rotor rpm passes the maximum allowable rpm, it is corrected by a slight collective up stick deflection. The pilot controls the forward speed with the cyclic. The autorotation phase can be further subdivided in two parts:

Tilting part: The helicopter pilot rotates the helicopter to the in advance defined autorotation pitch attitude. The in advance defined angular velocity depends on type of helicopter.

Steady autorotation: The rotor rpm is kept more or less steady and is corrected with a collective stick deflection if necessary. The steady autorotation is continued until a height of about 150 ft is reached.

Second Flare (D)

The objective of the second flare is to reduce the forward and descent speed. The second flare is a complicated and critical control manoeuvre. The second flare exists of three different parts.

Tilting part: The cyclic stick is pulled aft in order to achieve an in advance defined pitch attitude. The used angular velocity during the tilting manoeuvre depends on the type of helicopter and is defined in advance.

Steady flare: The rotor rpm is brought-up to the maximum achievable or maximum allowable rotor speed. The thrust vector points backwards and the forward speed decreases.

Collective check: At a height of about 20 ft a collective check is carried out. The collective stick is given a deflection of about 20% up. The forward speed decreases under the maximum allowable forward landing speed.

Recovery phase (E)

The objective of the recovery phase is to bring the helicopter in a slight nose up attitude and to reduce the descent speed below the maximum allowable touch-down speed. The recovery phase is started at approximately 10 ft height. The deflection of the collective is increased up to its maximum. The rotor rpm decreases. An optimal executed recovery phase gives the minimum allowable main rotor rpm at touch-down. The helicopter lands safely with a forward and touch-down speed below the maximum allowable.

Touch down and ground run (F)

The objective of the ground run is to stop the helicopter. The brakes are used to stop the wheel type helicopter.
The procedure to stop a skid type helicopter is different. After touch-down a certain deflection of the collective is maintained, so that the lift is less than the helicopter weight. The friction force between the ground and the skids decelerates the helicopter. Applying collective full down directly after touch down could result in toppling of the helicopter.

2.3 The autorotation starting with other initial conditions

Despite the different initial conditions, the pilot always tries to enter the procedure of the standard autorotative landing in one of the phases of paragraph 2.2, before or during the second flare. So the second flare, collective check and recovery are executed as in the standard autorotative flight. The variation of entering the autorotative flight starting with initial conditions other than standard are explained briefly. Use is made of the subdivision of the height-velocity areas of figure 1.

- Area B: At medium altitude and high forward speed the first flare is directly followed by a second flare. No steady autorotation is carried out in this case.
- Area C: At low level flights with high forward speed the priority is no loss of height. One flare with a collective check is carried out

before the pilot enters the recovery phase. During the flare the helicopter pilot is aware of height loss. A part of area C is a part of the forbidden area according to height velocity diagram. A little loss of height at very low flying levels with high speeds is fatal.

- Area D: In the lower part of the autorotative speed area one flare is carried out. The first flare is continued in the second flare. No steady autorotation is carried out.
  In the higher part of this area a steady autorotation is carried out before the second flare. The remaining flight is executed as described before.
- Area E: At high altitudes and low speed the priority is to gain speed. The pilot pushes the cyclic stick forward, so the helicopter gets a nose down attitude. When the helicopter reaches the autorotative speed, the pilot executes a steady autorotation. The remaining autorotative flight is executed as in the standard autorotative flight.
- Area F: At medium height and low forward speed the helicopter is in the middle of the "forbidden" area of the height-velocity diagram. According to the height velocity curve, no safe landing is possible in a large part of this area.
- Area G: At comparative high altitude and low speed the priority is to maintain main rotor thrust. The collective pitch is reduced to reduce the main rotor rpm decrease. An attempt is made to execute the recovery phase and to land safely. No flare is carried out. According to the height velocity curve, no safe landing is possible in a large part of this area.
- Area H: At low flight levels and low forward speed the priority is to keep course. The helicopter enters directly the recovery phase.

3 Description of the Mathematical Model

A programme was developed to calculate helicopter flight trajectories from the moment of engine failure up to touch down. It was assumed that the flight velocity vector remain in the helicopter symmetrical plane. To start with, flight trajectories have been calculated for initial flight conditions of the area's with a forward speed larger than the autorotative speed and a height above 150 ft.

The calculations are based on the energy concept. Energy of one kind can be exchanged for that of an other. For example, a decrease of kinetic rotation energy, by a decrease in rotor rpm, can be exchanged for a decrease in descent speed.
The helicopter is simulated by a point mass model in its centre of gravity with forces acting on it. The helicopter model is flown in the vertical plane of the earth axes. The point mass motion is controlled by variation

of the main rotor thrust vector (angle and magnitude). See figure 3 for the definitions.

3.1 Energy Concept

The energy concept is used for the calculations. During the autorotative flight the supply and demand of energy is in equilibrium.

$$P_{av_{eng}} = P_{req_T} + m\,g\,\frac{dh}{dt} + m\,V\,\frac{dV}{dt} + I_{rot}\,\Omega\,\frac{d\Omega}{dt} \tag{1}$$

The kinds of power contributing to this equilibrium will be briefly discussed hereafter. Detailed information of the used energy concept is given in reference 1.

Power available

The power available of the engine during the autorotative landing is equal to zero. The decline of engine power can be defined in several ways: a smooth decline or an abrupt loss of power. The abrupt loss of power represents the worst situation and is used in the mathematical model.

Power required

The power required is calculated by a combination of momentum theory for the rotor induced power and a simple blade element theory for the rotor profile power (reference 2). The rotor induced velocity is calculated according to the theory of Shaydakov (reference 3). The power required calculation is based on the thrust magnitude.

$$P_{req_T} = (P_{mr} + P_{tr})_T + P_{par} + P_{acc} + P_q \tag{2}$$

The various contributions to the power required calculation are:

Main rotor power: Two power contributions to main rotor power are defined for the calculations.

- The rotor induced power is calculated with $P_i = k_i\,T\,v_i$. T is the actual rotor thrust. k_i is the induced power factor accounting for non uniform induced velocity distribution, tip loss effects, etc. The mean induced velocity v_i is calculated using the method of Shaydakov.
- The profile power is based on the rotor thrust and a mean blade angle of attack. The profile drag of the airfoil,

	used for the profile power calculation, is expressed in a closed form and includes Mach and stall effects.
Tail rotor power:	The tail rotor induced power and profile power are calculated in a similar way as for the main rotor. The tail rotor induced velocity is assumed only to be dependent of the tail rotor thrust. This calculation is only used for the initial conditions. In the autorotative flight the tail rotor power is very small and assumed to be a small percentage of the main rotor power.
Parasite Power:	The parasite power is the power required to overcome the parasite drag of the helicopter fuselage.
Accessory Power:	The accessory power is the power used for all the accessories in the helicopter, e.g. flight instruments, electronic devices etc.
Tilting Power:	Rotation of the rotating main rotor and helicopter fuselage about the pitch axis requires power. This will be called the tilting power.

The power required calculation method provides an accurate basis for helicopter performance and flight trajectory calculations.

Internal power

The internal power is described by the last three components of equation 1. The internal power is the power derived from the energy stored in the helicopter itself. Three different kinds of energy can be distinguished. The height of the helicopter accounts for the potential energy. The horizontal and vertical velocity accounts for the kinetic energy. The main rotor speed accounts for the kinetic rotation energy. These kinds of energy fulfil the demand of power of the helicopter in the autorotative flight. If a temporary surplus of energy occurs during the execution of one of the phases, it is generally stored as kinetic rotation energy in the rotor system.

Substitution of the power required equations and the equations of motion in x and z direction (figure 3) into equation 1 gives the relation between the main rotor rpm change, tilt angle Θ of the rotor thrust vector and the magnitude of the rotor thrust for given flight speed components V_x and V_y.

$$P_{av_{eng}} = (P_{mr} + P_{tr})_T + P_{acc} + (\frac{1}{2} I_{rot} + I_{fus})\ q \frac{dq}{dt} + TV_x \sin\theta - TV_z \cos\theta + I_{rot}\Omega \frac{d\Omega}{dt} \quad (3)$$

3.2 Energy exchange in the standard autorotative flight

In each phase of the autorotative flight the exchange of energy takes place. First of all the potential energy is used to fulfil the demand of power required for flight. Secondary kinetic rotation energy is stored to be used during the recovery phase for deceleration. The energy exchange during the phases of the standard autorotative flight are discussed hereunder.

Engine failure/reaction time (A): Rotor kinetic energy is used to fulfil the demand of the helicopter power required. This means a rpm drop to fulfil the power demand.

First flare (B): The decrease of helicopter kinetic energy in the form of flight speed will fulfil the demand of power required. Some of the energy is stored as kinetic rotation energy in the main rotor. The main rotor rpm increases.

Autorotation phase (C): The height decreases, potential energy fulfils the demand of the helicopter power required. The main rotor rpm remains constant.

Second flare (D): For the first two parts of the second flare the decrease of kinetic energy will fulfil the demand of power required and rotation power; so the rotor rpm increases. In the collective check rotor kinetic energy is used to increase the trust in order to decrease the horizontal and vertical speed.

Recovery phase (E): In the recovery phase rotor kinetic power is used to fulfil a decrease of the descent speed.

3.3 Control Model

The control model was developed, based on the information acquired during interviews with helicopter test pilots. It appears that in actual flight the pilot controls the helicopter using the cyclic and collective stick. In fact this means that the helicopter flight path is controlled by variation of the thrust angle and magnitude with a feedback of pilot cues. The pilot uses the following cues during a scheduled symmetrical autorotative landing:

- course of the helicopter (reaction phase);
- main rotor rpm;
- the indicated airspeed (at low levels the ground speed);
- the pitch attitude of the helicopter;
- the height above the landing surface;

Different combinations of pilot cues are used in each phase of the standard autorotative flight. The activation of the following phase depends on an additional pilot cue which characterises the end of the current flight phase:

- the first flare ends when the autorotative flight speed is reached;
- the steady autorotative flare ends when a certain height above the ground is reached;
- the second flare ends after the execution of the collective check at a certain height;
- the recovery phase ends at the moment the helicopter touches the ground.

In figure 4 a time history is given of the global relation between the control actions and the major pilot cues of a standard autorotative landing.

The flight path is influenced by constraints within which the manoeuvre can be performed. The constraints are:

- a delay before control actions is given; different delay times for the collective and cyclic control in accordance with the reaction times required in the FAR or Mil. STD;
- a maximum and minimum allowable pitch rate;
- a maximum and minimum allowable main rotor rpm;
- a maximum horizontal and vertical speed at touch down.

The control parameters in the mathematical model are the mean blade pitch of the main rotor and the thrust vector tilt angle. The mean blade pitch is related to the thrust magnitude and the collective stick position. The thrust vector tilt is related to the pitch attitude of the helicopter fuselage. The manoeuvre calculation starts at the moment of engine failure. At the moment of engine failure the helicopter has a given acceleration, speed and main rotor rpm. With the equations of motion in x and z direction (figure 3) all unknown parameters, like mean blade pitch angle of the main rotor, thrust vector tilt, thrust vector magnitude and all power contributions are calculated. The mean blade pitch angle and the thrust vector tilt angle vary through the sequence of phases, following the defined pilot cues, which have been defined in advance.

3.4 Flight Path Calculations

The flight path is calculated by integration from one time step to the other. At the moment of engine failure, the power available is in equilibrium with the power required. The initial power required is determined. After the engine failure the power available is equal to zero. With equation 3 the decay of main rotor rpm is calculated.
For the next time step the main rotor thrust, acceleration, speed and the power required can be determined. A Newton Raphson iteration method is used to prevent the use of the induced velocity of the previous calculation step. The effect of the airflow direction on the drag is taken into account.

4 Results

Following the setting up of the model in the framework of the same MSc thesis at Delft University of Technology, Department of Aerospace Engineering (reference 4), a computer program was developed to make the actual calculations.

The computer programme was written in Borlands Turbo Pascal 6.0 and runs on personal desk computers. The computer programme is composed of two parts:

- Helidata: This part adjusts the input of the helicopter data and control information. The helicopter data consists of all the relevant technical data required for power calculations. The control information covers all the information about the control inputs for each possible phase of an autorotative landing.
- Autorot: Autorot is the flight trajectory calculation programme. The symmetrical flight is calculated by solving the equations of motions in the vertical plane. The change of the main rotor rpm is calculated by the power required equation discussed in the next paragraph. The nature of the autorotative landing is preprogrammed. This will not imply an objection because the actual flight path is governed by the chosen values of the control parameters.

A plotting programme was available in order to plot the results of the calculation.

As an example the results of a calculation with the computer programme for a light helicopter are presented in figures 5 to 7.

Figure 5: This figure shows the time history of the flight phases and the control actions. After the engine failure ($t = 0$) a different delay in control actions for the cyclic and collective control is visible.

Figure 6: This figure shows the change in main rotor rpm and the decay in height as function of time. The decay of the main rotor rpm during the collective check and the recovery phase is obvious.

Figure 7: This figure shows the time history of the descent and total speed. The decay of the total air speed during both flares is evident. The reduction of the descent speed during the collective check and the recovery phase is clearly visible.

5 Concluding Remarks

A computer simulation program for the calculations of the flight path for a helicopter in autorotative landing was developed. The development of the present calculation method was performed in the framework of a MSc thesis at Delft University of Technology, Department of Aerospace Engineering. An important aspect of this study was to select a suitable control model for the calculation of an autorotative flight path. The results so far are very promising. Because of the limited time available for this study, the following features in the calculation method and interface unit are not implemented yet:

- Non-linear variation of the thrust vector.
- Improved power required calculation for a specific helicopter type. A improved power calculation is essential for accurate trajectory calculations. Use of a power matching technique may be a good approach.
- Integration of the calculation program with a plotting facility, in order to make the results of the calculations directly visible on the computer screen.
- An automatic iteration routine to determine the most optimal control actions in the several flight phases. Such a partial optimisation routine is already in use for the one engine inoperative performance calculations of helicopters at the NLR, (reference 5).

6 References

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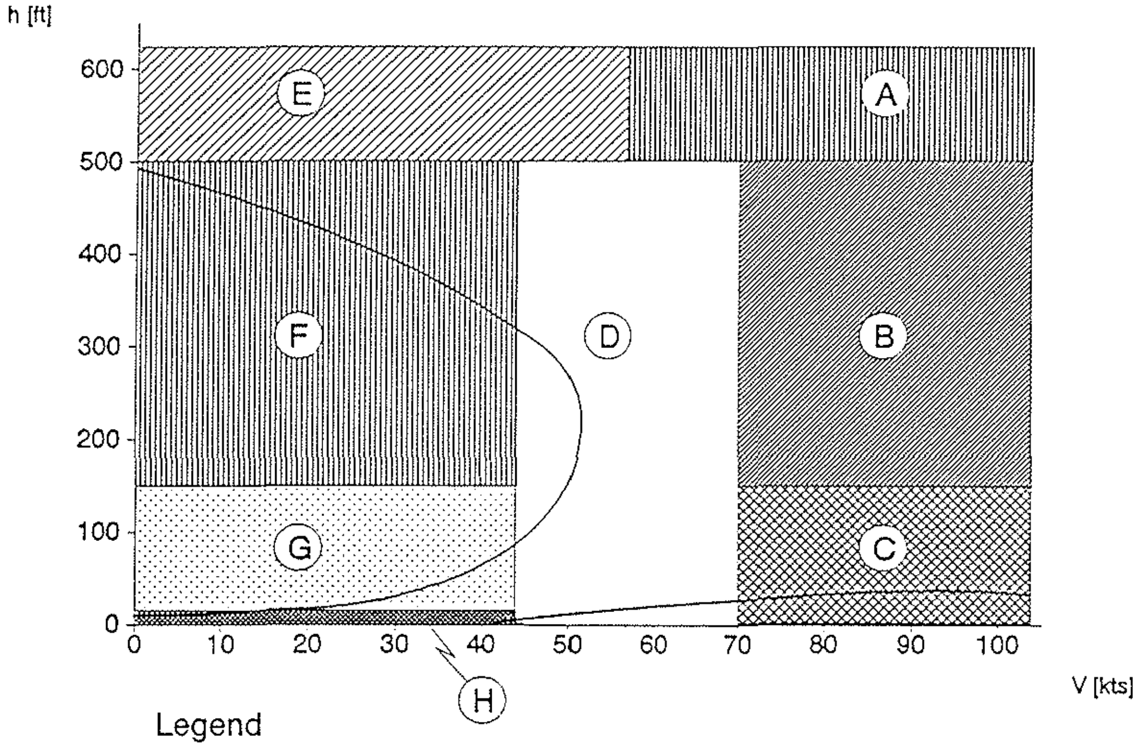

Legend

A: high altitude and high speed
B: medium altitude and high speed
C: low altitude and high speed
D: autorotative speed
E: high altitude and low speed
F: medium altitude and low speed
G: comparative high altitude and low speed
H: very low altitude and low speed

Figure 1: The subdivision of the height velocity areas.

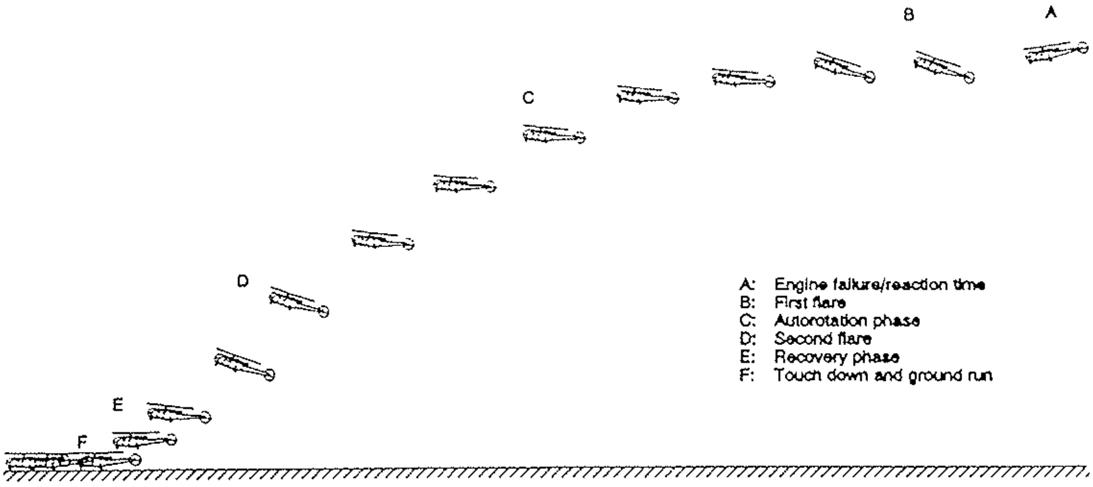

Figure 2: General lay out of the standard autorotative flight.

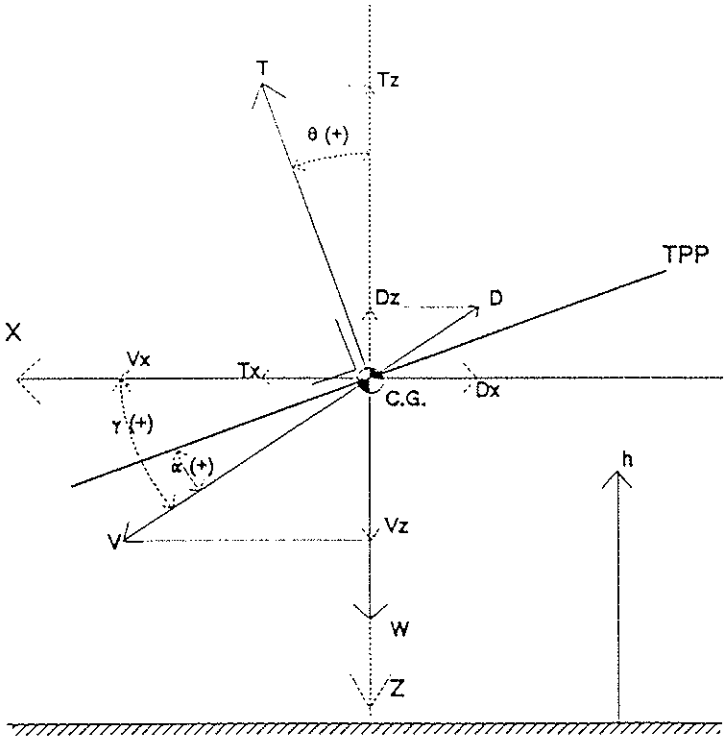

Figure 3:Definition of angles and forces.

V > 70 kts, h > 150 ft, Areas A & B

Independant Control Par.		Pilot Cues		
Θ	Θpr	V	h	rpm
Engine Failure	Engine Failure	Engine Failure	Engine Failure	Engine Failure
t = 0				
reaction time	reaction time	V > Vaut	h > 150 ft	rpm = 100%
thrust vector backwards				
	Lower Θpr till Θpr min			rpm as high as possible with a max. of 118 %
		V=Vaut + 5kts		
thrust vector in autorotation attitude				
thrust vector constant attitude	vary Θpr to correct the rotor rpm.	V = Vaut		rpm ≈ constant
second flare, thrust vector backwards			h ≈ 150 ft	rpm as high as possible with a max. of 118 %
	Θpr setting of 20 %	V = 20 ã 30 kts		
recovery phase, thrust vector vertical			h = 20 à 30 ft	
	bring Θpr to maximum setting Θpr max			rpm = 70 %
$t = t_t$				

Figure 4: Time history of the control parameters in combination with the pilot cues for a light helicopter (V > 70 kts and h > 150 ft).

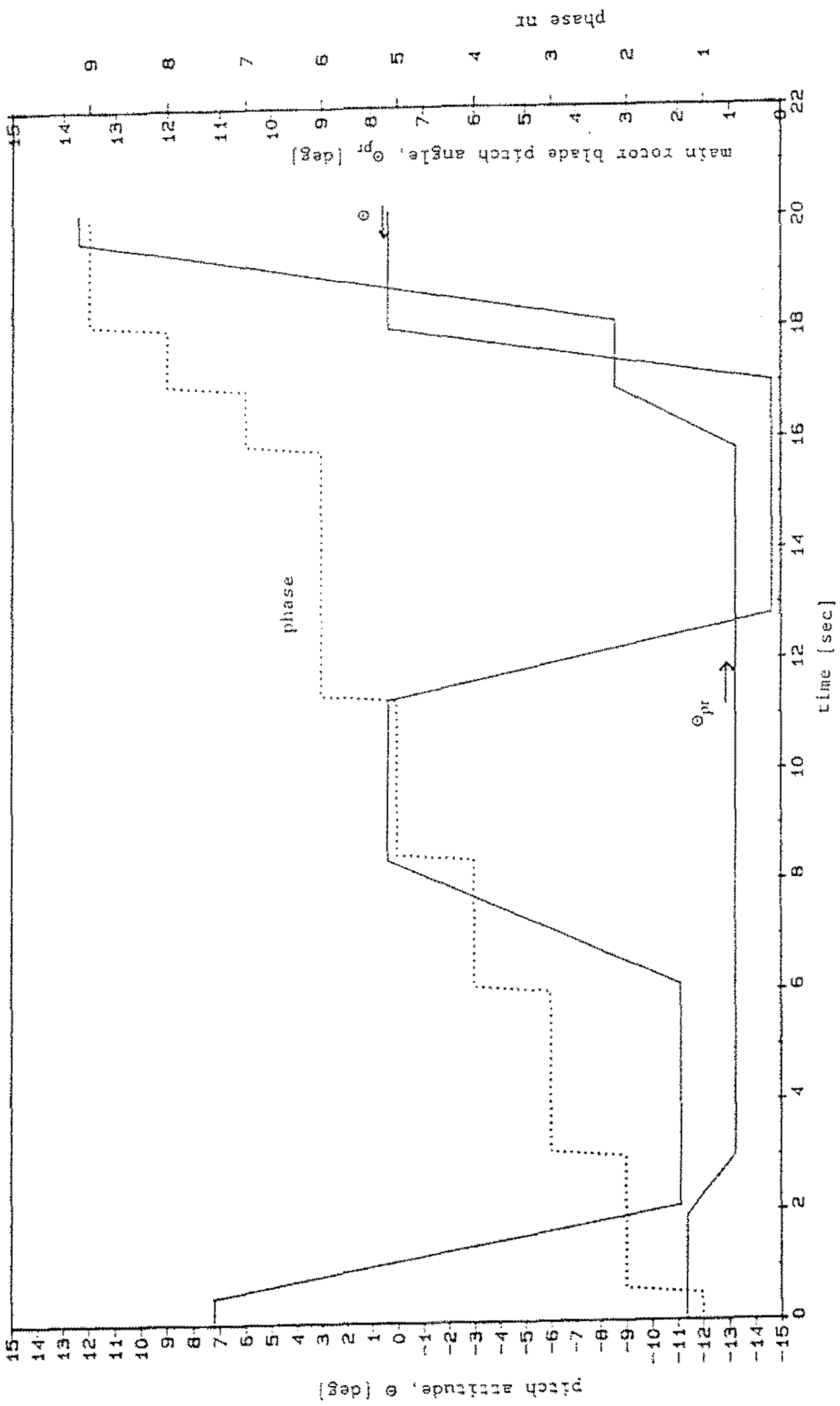

Figure 5: Control actions and phases as function of time.

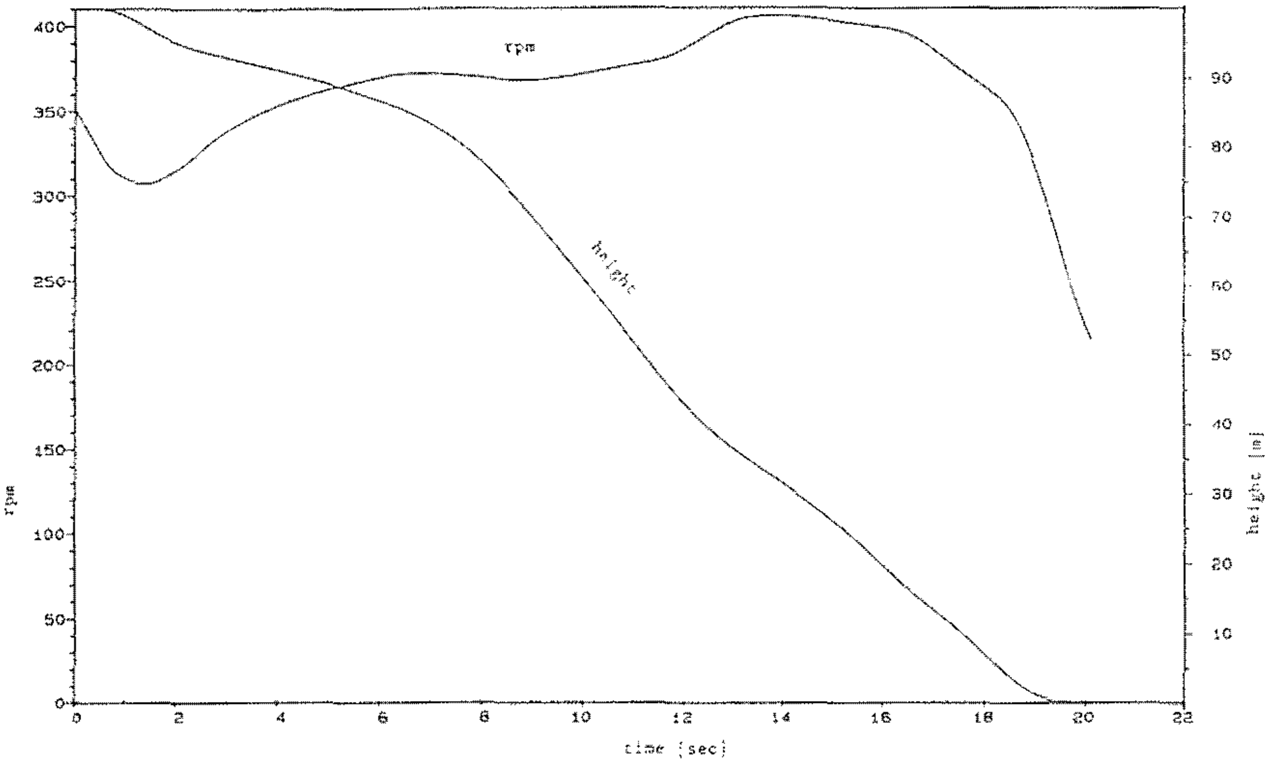

Figure 6: Rpm and height as function of time.

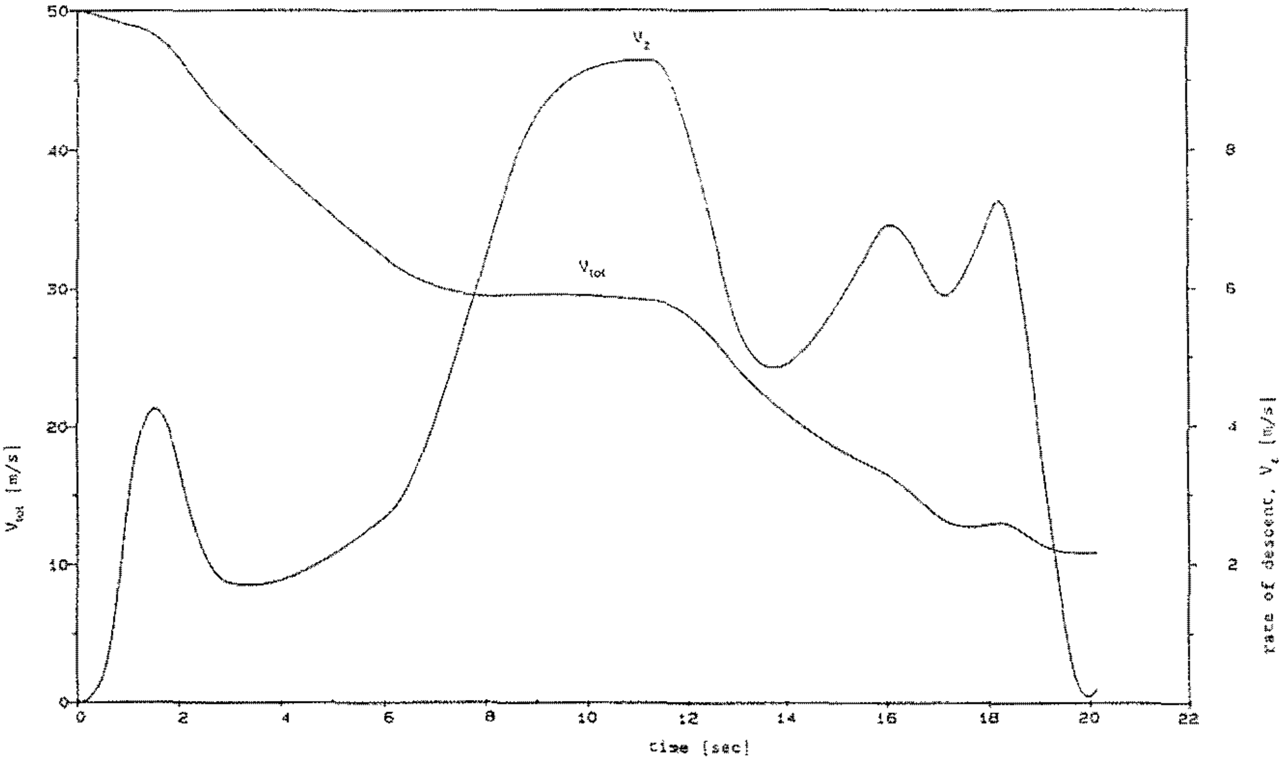

Figure 7: Velocity and rate of descent as function of time.