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INVESTIGATION ON HELICOPTER STEEP APPROACH

- FLIGHT PATH ON-BOARD PLANNING AND CONTROL-

BY

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Abstract

Takeoff and landing are critical flight situations. A steep approach into a confined area with bad visibility and extreme weather conditions decreases the flight safety. A well planned safe flight path reduces pilot's workload and the safety risk.
The "steep" approach is a favourable alternative to the "normal" flat approach, when the helicopter specific characteristics are used. Conditional on their possibility to hover, their vertical descend and climb ability, helicopters can fly straight lined and curved flight paths. Various approaches are restricted by flightmechanical boundaries and certification requirements. Strict flightmechanical boundaries are the vortex ring state and the autorotation boundary. Further limitations may be the unsafe area of the height-velocity diagram, the passenger comfort and the cockpit view.
The paper presents a code, which calculates a safe trajectory from an arbitrary point in the air to an arbitrary landing point under consideration of the described boundaries. Because there are various boundaries and requirements depending on the height above ground, the approach path is split-up in several segments. A landing system, giving information about the present position and altitude, is necessary to follow these trajectories. In view of curved flight paths, especially the Microwave Landing System (MLS) and the Global Positioning Sytem (GPS) are two suitable landing systems. An input-output interface for these systems is implemented in the code.

The pilot needs adequate displays, which indicate the flight path difference, the airspeed and the rate of descent difference between commanded and actual values. With reference to a survey among pilots a flight guidance display was developed. Supplementary to a pilot controlled flight it is possible to automate helicopter steep approaches. A control concept with predetermined controls - computed by an "Inverse Simulation" - and an attitude flight path controller will be presented in this paper.

Notation

$A-H$	transition points
$\underline{F}$	force vector
G	helicopter weight
H	height
H_{Geoid}	height above geoid
$\underline{\underline{I}}$	inertia matrix
$K_{(x,\ldots,\Psi,p,q,r,u,v,w)}$	feedback gains
m	helicopter mass
$\underline{M}$	moment vector
n_z	load factor
P	power
R	slant distance
$\underline{R}_g$	position in geodetic axis
R_{MLS}	slant distance of the MLS
s	Laplace operator
$S_{xy,g0}$	unwind flight path
t	time
T	thrust
$\underline{\underline{T}}$	derivative matrix
$\underline{T}_{Res.}$	residual trim values
$T_{(x,\ldots,\Psi)}$	time constants
V	airspeed
V_{BLSS}	balked landing safety speed
$\underline{V}_g$	velocity in geodetic axis
$\underline{V}_{Kg}$	flight path velocity in geodetic axis
V_{TOSS}	takeoff safety speed
$\underline{V}_{Wg}$	wind velocity in geodetic axis
$V_{xy,g}$	horizontal airspeed
V_y	velocity for maximum climb rate
$\dot{\underline{V}}$	acceleration
$\dot{\underline{V}}_{Kg}$	flight path acceleration in geodetic axis
w_g	rate of descent
x, y, z	Cartesian coordinate axis
γ	flight path angle
γ_{MLS}	elevation of the MLS
$\underline{\vartheta}$	controls $\underline{\vartheta} = (\vartheta_0, \vartheta_C, \vartheta_S, \vartheta_{TR})^T$
$\vartheta_{0,TR}$	collective pitch (rotor, tail rotor)
$\vartheta_{C,S}$	cyclic pitch
λ	longitude
σ	build-in rotor shaft angle
$\underline{\Phi}$	Euler angles $\underline{\Phi} = (\Phi, \Theta, \Psi)^T$
φ	latitude

χ	flight path azimuth angle
χ_{MLS}	azimuth of the MLS
$\underline{\Omega}$	body rates $\underline{\Omega} = (p, q, r)^T$
$\dot{\underline{\Omega}}$	rotation acceleration

Subscripts:

A	arbitrary point on geoid
$c.g.$	centre of gravity
$CG\ Body$	fuselage center of gravity
$De.$	determined
e	earth fixed
$Eng_{1,2}$	engine 1,2
f	body fixed
Fu	fuselage (aerodynamic)
g	geodetical
$g0$	geodetical, earth fixed
HS	horizontal stabilizer
min	minimum
R	position
Ro	rotor
RP	reference point
S	start
TR	tail rotor
V	velocity
VS	vertical stabilizer
Φ	Euler angles
Ω	body rates

Abbreviations:

ADAC	Allgemeiner Deutscher Automobilclub
ALT	Altitude
BGS	Bundesgrenzschutz
DGPS	Differential GPS
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
FAA	Federal Aviation Agency
FAR	Federal Aviation Regulations
FUS	Flugunfalluntersuchungsstelle
GPS	Global Positioning System
HDG	Heading
IAS	Indicated Airspeed
ILS	Instrument Landing System
LDP	Landing Decision Point
MLS	Microwave Landing System
MTOW	Maximum TakeOff Weight
VS	Vertical Speed
WGS84	World Geodetic Survey in 1984
Δ	Difference

1. Introduction

Helicopters are aircrafts, which are able to hover and to land or take off vertically. These possibilities allow them to realize approaches into and departures out of unprepared, confined areas. In contrary to "normal" flat flight path angles, "steep" flight path angles, e.g. at landing field surrounding obstacles, might be required. Such approaches are called "Steep Approaches". One advantage of these approaches is a small noise pollution area. Unfortunately in comparison to a "normal" flat approach the workload of the pilot rises, because the flying qualities of the helicopter change rapidly. Influence of wind, bad visibility like rain, snowfall or fog increases the pilot's workload additionally.
Target of our investigation is to reduce the workload of the pilot and furthermore to improve the flight safety by a safe flight path planned on board. If a pilot should follow a calculated flight path he needs adequate displays. Amongst the flight path differences he needs information about the airspeed, the ground speed, the heading angle as well as the rate of descent difference between the commanded and the actual values.
If it is possible to calculate a save flight path and also to supply the required control inputs - computed by an "Inverse Simulation" - the question arises, why shouldn't the entire steep approach profile be performed automatically? In this case the pilot only has to supervise the approach.

2. Steep Approach

2.1 Definition

Standard fixed wing aircaft approaches have to be realized with flight path angles between 2.5^o and 3.0^o. An approach with a flight path angle above 3.0^o will be designated as steep approach. There is no equivalent classification for helicopter approaches. Refering to the fixed wing aicraft classification, in the following helicopter approaches with a flight path angle between 3.0^o and 90.0^o will be defined as steep approaches. If a helicopter is licensed according to the Federal Aviation Regulations (FAR), the tested and approved approach procedures are recorded in the flight manual. Figure 1 shows the approach procedure for the MBB BO 105. The steep approach is split up into five stages depending on the height. Straight lined as well as curved flight paths are permitted (figure 2). An approach according to path "a" allows the pilot a permanent view to the landing point but is not appropriate if there are higher obstacles beside the landing area.

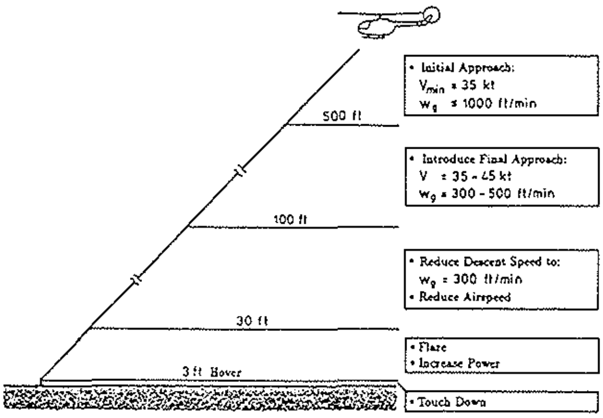

Figure 1: Steep Approach in Reference to the BO 105 Flight Manual [1]

A straight lined flight path according to "b" is the easiest task for the pilot. Path "c" is appropriate in the presence of higher obstacles and if no permanent view to the landing point is necessary.

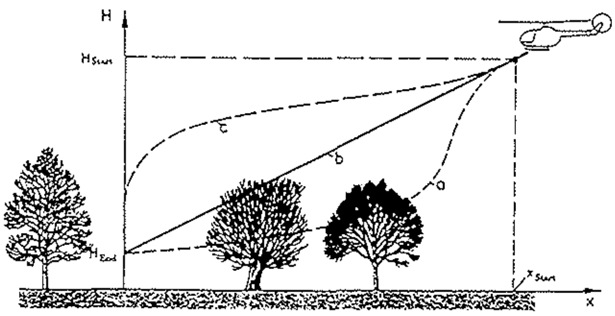

Figure 2: Steep Approach on Straight Lined or Curved Flight Path

2.2 Steep Approach Limitations

As shown before, the pilot's view to the landing point is restricted in very steep approaches. Less steep approaches with deceleration impair the pilot's view as well (figure 3). The pilot has to tilt back the thrust vector T of the rotor disk to reduce the airspeed. An increase of the angle of attack enlarges the pitch angle and this reduces the view downwards. A maximum load factor n_z of $1.15g$ for passenger comfort maybe a direct limitation to deceleration [2]. Therefore, in turns bank angles of less than 30^o are admissble. Additional limits given by the Federal Aviation Agency (FAA) are the FAR requirements. It has to be distinguished between FAR 27 (Normal Category Helicopter, Maximum Take Off Weight (MTOW): 2720kp), FAR 29 Cat. B (Transport Category Rotorcraft, MTOW: 9000kp) and FAR 29 Cat. A (Helicopters without a weight limit).

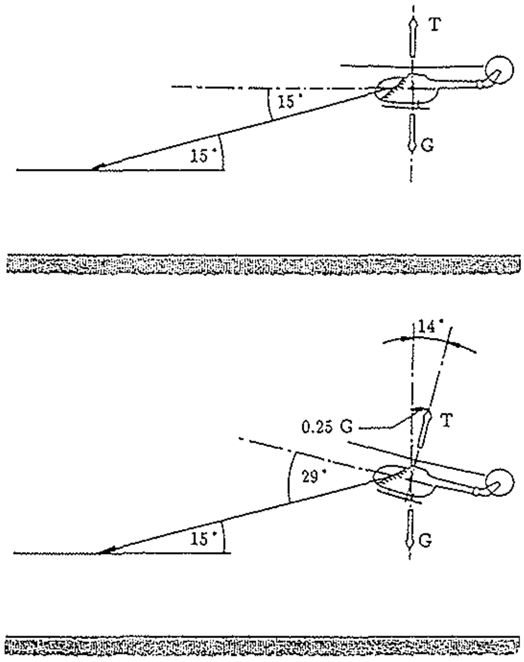

Figure 3: Visual Angle of Stationary and Decelerated Steep Approach

According to FAR 27 and FAR 29 Cat. B a helicopter has to be safely landed after an engine failure. Helicopters licensed according to FAR 29 Cat. A must be able to go around again before passing the landing decision point (LDP) and must be safely landed after passing the LDP.

Figure 4 shows a trajectory of a conventional and of a vertical landing according to FAR 29 Cat. A.

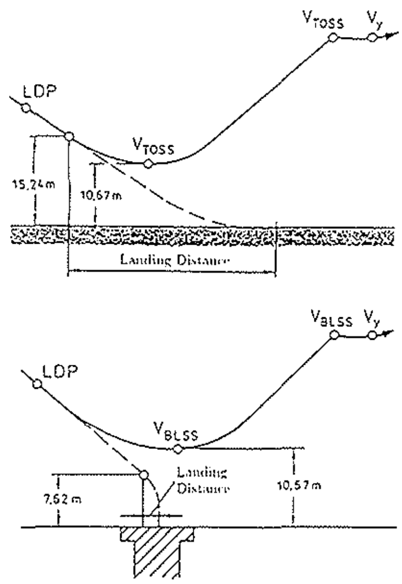

Figure 4: Category A Landing (Conventional, Vertical)

In case of an engine failure behind the LDP or no engine failure the approach has to be continued along the dotted line. An engine failure before reaching the LDP forces the pilot to accelerate the helicopter up to the takeoff safety speed V_{TOSS} or the balked landing safety speed V_{BLSS} at a minimum altitude of $10.67m$. After the helicopter reaches a specified altitude the speed has to be changed to the velocity for maximum climb rate V_y.

Additionally FAA demands the observance of the limits of the height-velocity diagram [2]. Figure 5 marks two areas that have to be avoided by the pilot corresponding to the helicopter licence. The high speed area is relevant for helicopters that loose height directly after an engine failure and don't pitch up. For the BO 105 this area is non-existent. The energy state within the unsafe low speed area, represented by the low hover point, the high hover point and the critical knee point, renders no change for a flare maneuver without exceeding the maximum allowable touchdown speed (max.: $1.53m/s$) requested by the FAA. For multi-engine helicopters the remaining power in this area is not sufficient to accelerate themselves up to V_{TOSS} [3]. The height-velocity diagram is influenced by the helicopter type, the helicopter weight and the atmospherical conditions. A generalization of the height-velocity diagram as developed by HANLEY and DEVORE [4] and validated by PEGG [5] allows the adaption to the specific conditions.

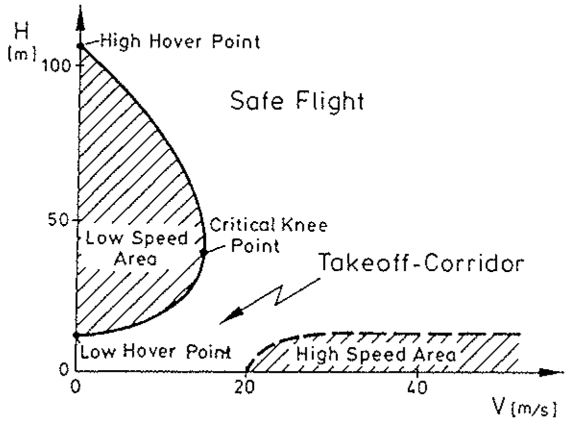

Figure 5: Height-Velocity Diagram

A strictly flight mechanic limitation is given by the vortex ring state (figure 6). This flight state occurs at low airspeed conditions in connection with a rate of descent equivalent to the induced velocity of the main rotor. High attitude oscillations and deminished control effects are caused by a turbulent flow. For the BO 105 the danger area occurs at velocities below $6m/s$ in connection with a rate of descent between $3m/s$ and $9m/s$ ([6], [7]).

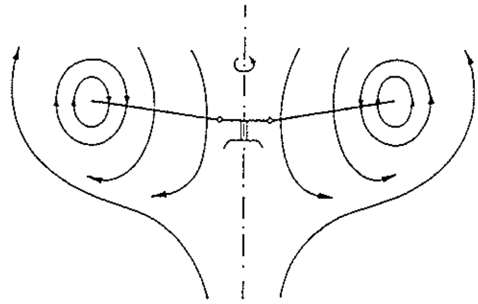

Figure 6: Vortex Ring State in Vertical Descent

In figure 7 a further relevant limitation to steep approach - the autorotation boundary - is shown. During the autorotation the potential energy of the helicopter is conformed into kinetic energy of the rotor. The rate of descent is mainly influenced by airspeed, mass of the helicopter, pressure height, rotor revolution and pitch control angle. The envelope of the curves shown in figure 7 represents the autorotation boundary, i.e. the minimum rate of descent depending on the airspeed at 100% rotor revolution. In reality the pilot cannot reduce the pitch control angle without racing the rotor revolution. Flight tests confirm the results of the theoretical investigation [8].

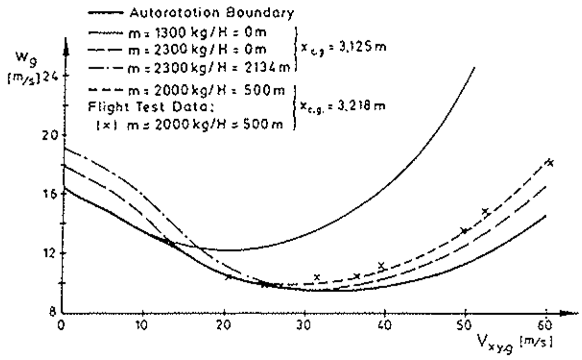

Figure 7: Autorotation Boundary

To point out the correspondence between simulation model and reality, figure 7 additionally shows the results of flight tests and simulation for a MBB BO 105 with a medium weight of $2000kg$ and an average flight altitude of $500m$. For a velocity below $20m/s$ the recording in the test is inaccurate, that means, deviations increase in that region. Thus the presentation concentrates the results above $20m/s$.

3. Flight Path Planning

The introduced flight path planning software enables the pilot to fly the helicopter safely on his trajectory from the moment of initiation (about 5 minutes before landing) to the moment of landing. It has to be possible to give starting position of approach, position of landing, flight directions and velocities flexibly.

As has been shown in chapter 2, steep approaches with a flight path angle between 3^o and 90^o are possible, but there are a number of limitations. For airports with landing systems, licensed paths are outlined in the approach charts. "Turns" and "Intercepts" need to be flown with a bank angle according to a 2 minutes 360^o "Turn". General rules for approach paths don't exist.

The adaption of the flight path data to navigation data, which is used for landing systems is a general precondition for the application of a flight path planning program. The Microwave Landing System (MLS) and the Global Positioning System (GPS), respectively the Differential GPS (DGPS) are Instrument Landing Systems (ILS), which allow to follow any flight path geometry. For input and output of MLS polar coordinates habe to be assigned.

Figure 8 shows the system of coordinates used for GPS navigation based on the earth frame, described by the "World Geodetic Survey" in 1984 (WGS84). The transformation of the polar coordinates according to WGS84 $(R, \lambda_A, \varphi_A)$ into the Cartesian coordinates of an arbitrary point, here A (x_A, y_A, z_A), which forms the base of the geodetic coordinate system (g_0) can be performed directly. Reversibly, the transformation of Cartesian coordinates into polar coordinates is an iterative process.

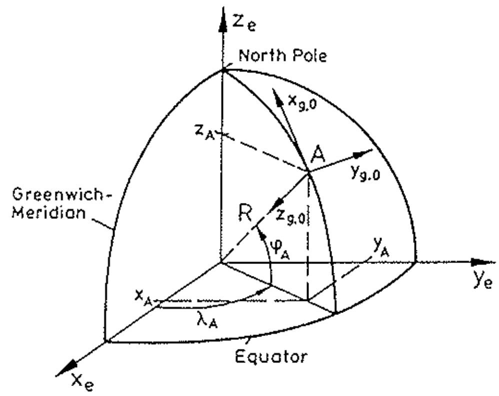

Figure 8: WGS 84 Čoordinate Systems

3.1 Segmentation of the Flight Path

The investigation is conducted to gain a safe flight path. To take into account the various conditions during different path sections, the complete approach flight path has to be segmented. By moving from one segment to the other, at the point of transition, different data for position, velocity and acceleration can be given. With reference to [1], figure 9a shows a possible segmentation of the approach path in a vertical perspective. Segment $\overline{HG}$ corresponds with the flight path distance between initiation and finished flight path planning, flown with constant velocity, flight direction and altitude.

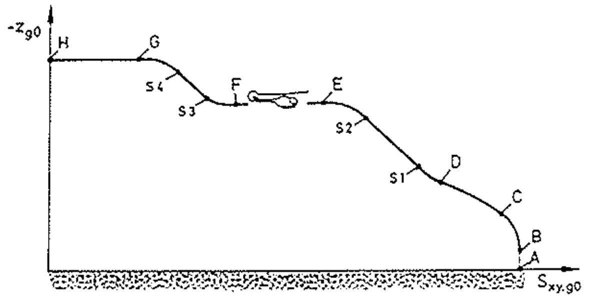

Figure 9a: Segmentation of the Approach Path in the Vertical Plane

Because of the possibility to approach from any height, it is necessary to reduce height down to a level, which has to be defined before. During segment $\overline{GF}$ up to transition point $S4$, the helicopter has to accelerate to the maximum admissible rate of descent. Subsequently the rate of descent has to be constant up to point of transition $S3$. Between $S3$ and F the rate of descent has to be reduced down to $0m/s$. With a low difference in altitude between G and F, it is sufficient to accelerate to a maximum possible rate of descent and immediately decelerate again. An approach speed at the starting point H, which is higher than the demanded speed in point F or point E, has to be decelerated in segment $\overline{GF}$. If the approach flight direction is different to the flight direction during the final approach, the flight direction has to be changed. This happens under consideration of the admissible accelerations in segment $\overline{FE}$ (figure 9b).

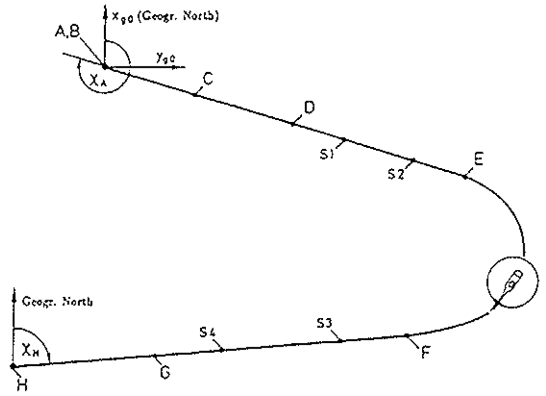

Figure 9b: Segmentation of the Approach Path in the Horizontal Plane

"Turns" with varying velocity and / or varying of rate of descent increase the work load of the pilot and decrease the flight safety. Thus change of flight direction should take place at constant altitude and velocity. After the "Intercept" the altitude has to be reduced in segment $\overline{ED}$ according to segment $\overline{GF}$ (except the rate of descent in point D). Subsequently the velocity has to be decreased continuously while altitude still is reduced. In case velocity is limited by the height-velocity diagram in C, this minimum velocity has to be considered for the calculations. Otherwise the velocity can be choosen. During the segment $\overline{CB}$ rate of descent and velocity have to be reduced to $0m/s$. Because the vertical touch down has to be performed directly by the pilot, segment $\overline{BA}$ is not planned.

3.2 Flight Path Planning Algorithm

It should be possible to use nearly any altitude or velocity at the transition points of the flight path. Thus accelerations have to be admitted within the segments. In reality helicopter cannot accelerate jerky or with a shock. Therefore the mathematical function describing the single segments has to be continuous. Higher degree polynomial functions meet this requirement as well as the limits can be considered, described in chapter 2. Furthermore all three coordinate directions of the flight path have to be planned indepently, under the condition that the total velocity doesn't oscillate. A sixth degree polynomial equation in each direction allows to consider all 18 marginal conditions, that means 3 positions, 3 velocities and 3 accelerations at each transition point. Additionally it is possible to smoothen the oscillation of the velocity by an optimization algorithm, which takes the 3 remaining parameters into account. The optimization is numerical [9]. The process of flight path planning is controlled by the program HPBAHN (figure 10).

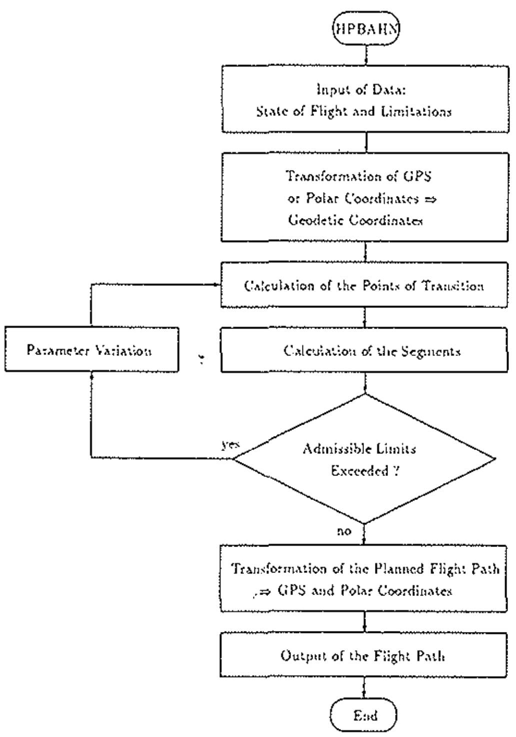

Figure 10: Flight Path Planning Algorithm HPBAHN

When the first subroutine is started, the program has to be fed with approach and landing position, defined limits, points of transition and data of the flight situation. If the approach position does not exist as geodetic $g0$-coordinates, it has to be transformed. Then the positions of the points of transition are estimated, considering the admissible limits. In case of violation of these limits between the points of transition, e.g. exceeding the admissible acceleration, the transition points are calculated again using different parameters, and the calculation of the segment is repeated with the new transition points. The last step is the transformation to GPS and polar coordinates. As an example an approach to St. Petersburg is outlined in figure 11. The approach starts from an altitude of $700ft$ ($213.4m$) in eastward direction with a "Heading" of 110^o and a velocity of $55.4kt$ ($28.5m/s$). Then velocity and altitude are reduced while flight direction is kept constant, as has been described in chapter 3.1. It is obvious, that acceleration stays below the admissible load factor of $1.15g$ ($11.3m/s^2$) and the rate of descent does not exceed the maximum of $1000ft/min$ ($5.1m/s$), which is defined in the flight manual. As result of the high comparable rate of descent a large flight path angle is produced. During the "Turn", when the helicopter has to be conveyed to the final appoach direction, velocity and altitude stay constant. After reaching the final approach direction the rate of descent is increased again in order to reduce the altitude. In this flight path segment, rate of descent has to be $500ft/min$ ($2.5m/s$) maximum. At an altitude of $100ft$ ($30.5m$), the rate of descent is decreased to $300ft/min$ ($1.5m/s$). Velocity stays constant. In the following from an altitude of $30ft$ ($9.1m$), rate of descent and velocity are reduced to $0m/s$. Figure 11 also points out the parameters, which are necessary for navigation with a MLS or GPS system. The parameters for DGPS are the altitude above the geoid, the latitude (ca. $59^o48''$) and the longitude (ca. $30^o16''$) (airport St. Petersburg). The slant distance R, the azimuth χ and the elevation γ are the required parameters for navigation with MLS.

4. Control

4.1 Pilot Controlled Approach

When the approach path has been calculated by the flight path planning program, the pilot has to be given an instument, which prepares this information in a way, that enables the pilot to follow the trajectory. For guidance tasks it is helpful to display the flight path data such as, position, velocity and flight direction as well as the adequate Euler angles. Information, that enables the pilot to recognize the necessary flight maneuver in advance, helps the pilot to follow the determined path exactly. The design of a concept, which shows the necessary data for guidance on a display, is to be seen in figure 12.

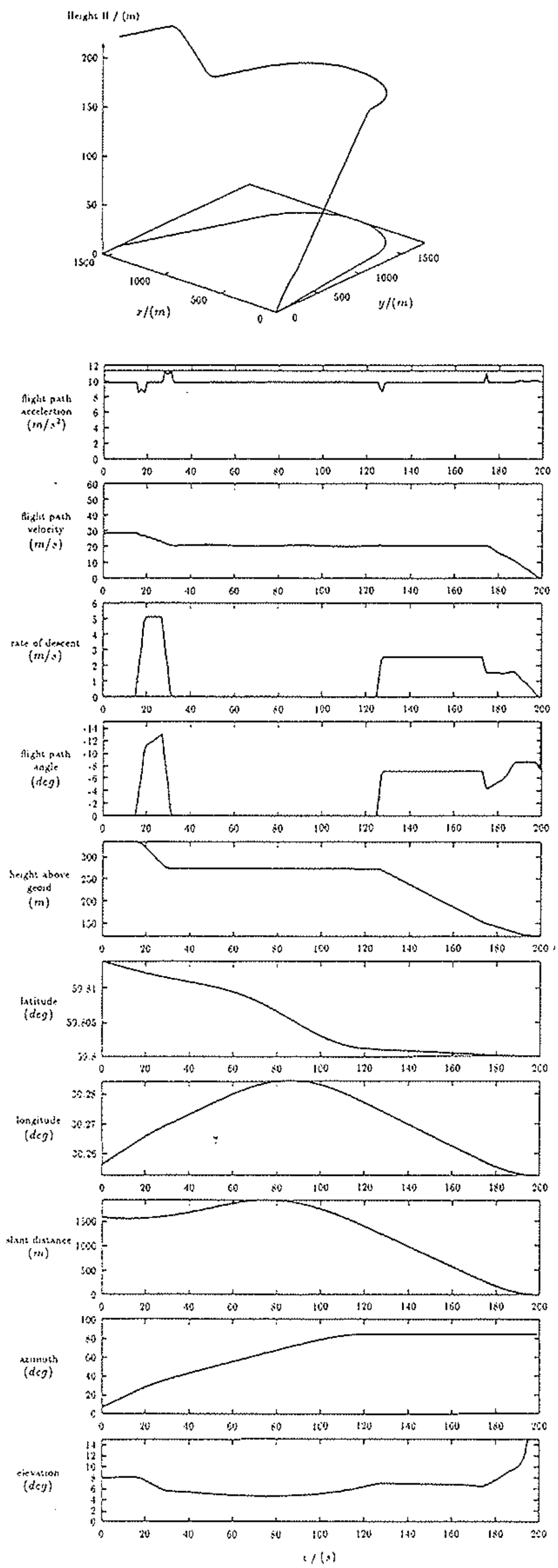

Figure 11: Example of an Approach Path

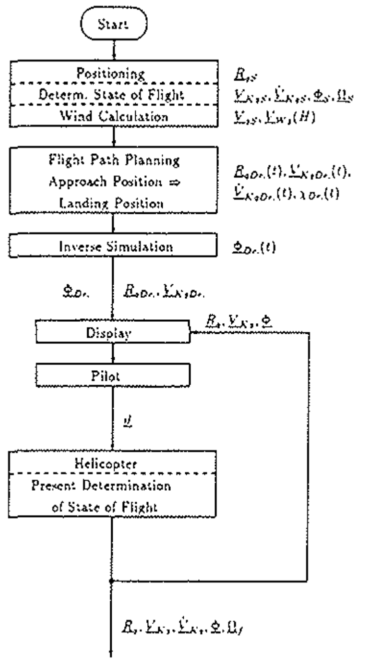

Figure 12: Pilot Controlled Approach Concept

After the algorithm has been started, the position $\underline{R}_{gS}$ is determined, using one of the landing systems described above. At the same time, the flight condition has to be identified in terms of flight path velocity $\underline{V}_{KgS}$, flight path acceleration $\dot{\underline{V}}_{KgS}$, Euler angles $\underline{\Phi}_S$ and body rates $\underline{\Omega}_S$. The actual wind velocity is specified by subtracting velocity $\underline{V}_{gS}$ from the flight path velocity. A simple approach allows to approximate wind as a function of height $\underline{V}_{Wg}(H)$. Subsequently, the presented flight path planning algorithm is used to determine position $\underline{R}_{gDe.}$, flight path velocity $\underline{V}_{KgDe.}$, flight path acceleration $\dot{\underline{V}}_{KgDe.}$ and the flight path azimuth angle $\chi_{De.}$ as a function of time. An inverse helicopter simulation model, that will be described in the following, allows the calculation of the expected Euler angles $\underline{\Phi}_{De.}$ of the helicopter. Determined position, velocity and Euler angles are presented on a display and set against the present data of the flight condition. Deviations between determined and present data of the flight condition have to be adjusted by the pilot, using adequat control inputs $\underline{\vartheta}$. The helicopter will react according to the control inputs. Changes of the flight conditions are shown on the display.

4.2 Display

In the era of microelectronics and the relating possibilities of presentation in aviation computerbased displays are more and more accepted. An example is the Airbus family ([10], [11]). Investigations in helicopter technology are partly moving into this direction ([12], [13]), too. In addition to conventional display instru-

ments, displays that can be used for flight guidance are in development ([14], [15]). Future developments will be supported by moving map displays.
The following two displays are designed to enable a pilot to follow a given flight path. Necessary elements of the display are height above ground, rate of descent, velocity, heading as well as pitch angle and bank angle and the position along the approach path. Extensive inquiries among 7 pilots of ADAC, BGS, DLR and FUS about their opinion of display elements were part of the design process. A number of different displays were presented, such as bar with pointer, circular dial, numerical display, scale display as well as possible profile situation displays and tunnel displays. The display possibilities and potential combinations of each display element have been presented and commented by the pilots in view of rate of reading, accuracy of reading and required space. Although the circular dials, as shown in figure 13, correspond more or less with the conventional indicators and therefore less training would be necessary, most pilots supported the bar and scale displays (figure 14).

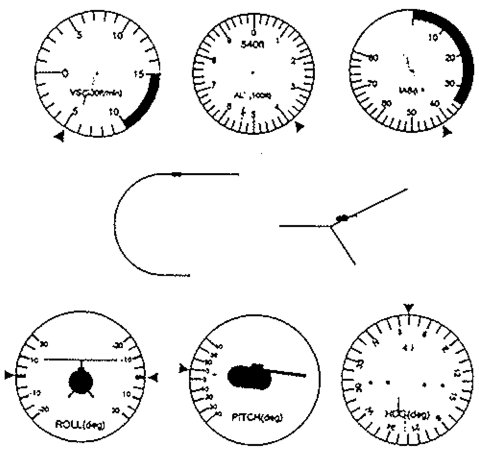

Figure 13: Display with Circular Dials

The presentation of calculated flight path data and Euler angles occur in both concepts by bugs. Unadmissible areas are marked red (here dark gray). Figure 13 shows a two dimensional projection of the approach path. This projection was commented by the pilots to be less clear, than that of figure 14. In addition to a projection of the unwind flight path, shown in figure 14, a tunnel display is used to describe the approach. The outward frame is fixed and the frames inside seem to come towards the pilot. Corresponding bank angles are considered.
The altitude display in figure 14 consists of a fixed scale for an altitude from 0 to $1000 ft$ and a blue U-bug (here gray), which gives calculated height above ground. Furthermore it contains a green bar with pointer and a numerical indication (here light gray), which shows the present height. The U-bug sets the admissible range of altitude, which defines the limitation for the present altitude. When arriving at the ground, the numerical indicator can be used for a detailed display.

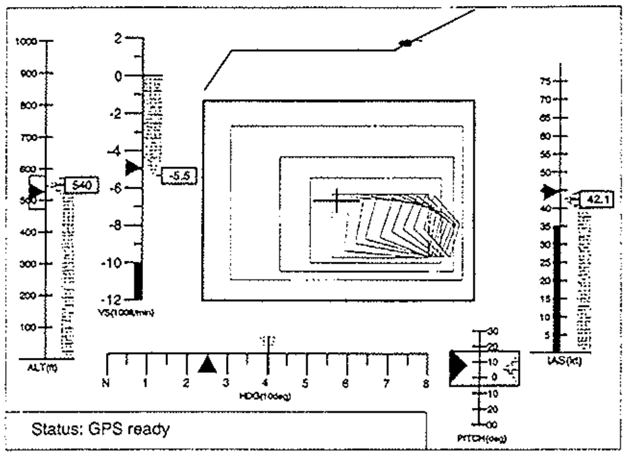

Figure 14: Scale Displays with Tunnel Display

Depending on the altitude, the unadmissible area is marked by red limitation bars on the vertical speed scale. The arrow-head of the green bar additionally indicates, if the helicopter is descending or climbing presently. While the altitude and the velocity displays use fixed scales, for displaying of heading (HDG) and pitch, movable scales are employed. The determined values are shown by a blue the present by a green bug. For display of airspeed (IAS) area limitations depending on height are implemented, too. A standard PC is used for the presented investigations.

4.3 Automated Approach

As shown in chapter 4.1 the inverse helicopter simulation model can calculate the expected Euler angles for a flight path in advance. Furthermore the program computes the necessary control inputs in order to follow a given flight path. In this case, flight condition determines the controls. In contrary to a simulation, where the flight condition is deducted from the controls, this refers to an inverse simulation ([16], [17], [18], [19], [20] and [21]).
If the necessary controls can be defined this way in order to follow a given flight path, it is possible to automate the approach completely. The pilot's task simply is, to supervise the process. With reference to the concept, where the pilot follows a given trajectory by using a display, in figure 15 the concept of an automated approach is drawn. While calculation of position, flight condition, wind and flight path planning remain unchanged, the inverse simulation is distinguished by the additional determination of controls $\underline{\vartheta}_{De.}$, body rates $\underline{\Omega}_{De.}$ as well as derivatives $\underline{\underline{T}}$. These derivatives represent the linearized dependency of forces and moments respectively inputs of controls

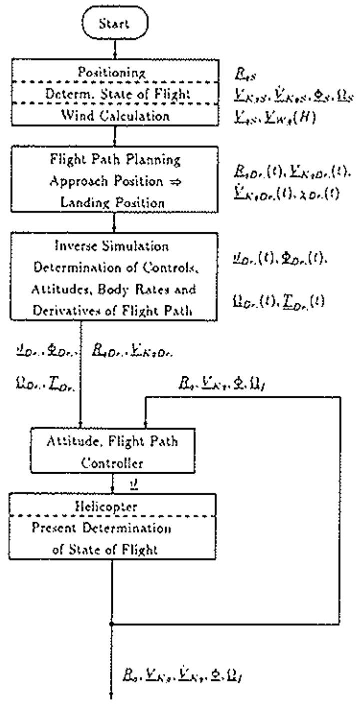

Figure 15: Automated Approach Concept

and Euler angles and are an instrument for decoupled control of the helicopter movement. Together with the results of the flight path planning, the data of the inverse simulation is fed into an attitude flight path controller, which determines the necessary controls for the flight path guidance of the helicopter. The attitude flight path algorithm has to be described later, taking into account the present flight condition. The data of flight condition, adapted by the helicopter, is transfered to the controller by specific measurement equipment. For development and validation of this concept, instead of a real helicopter, a simulation model, which has been validated by flight tests will be used. The simulation model will be described in the following.

4.4 Helicopter Simulation Model

The helicopter simulation model "HUB212" [22], used for the investigations, is based on the data of a MBB BO 105. Several flight tests permit the adaption of the model to reality. For an example see figure 7. An entire six body-degree of freedom equation describes the helicopter motion. These equations are numerically solved by the integration of translational and rotational accelerations. The equations of motion can be described in vector form:

$$m \cdot \left(\dot{\underline{V}}_{Kf} + \underline{\Omega}_f \times \underline{V}_{Kf}\right) = \sum \underline{F}_f \qquad (1)$$

$$\underline{\underline{I}}_f \cdot \dot{\underline{\Omega}}_f + \underline{\Omega}_f \times \left(\underline{\underline{I}}_f \cdot \underline{\Omega}_f\right) = \sum \underline{M}_f \qquad (2)$$

The different components of the model, such as rotor, tailrotor, fuselage and empenage, are defined by their forces and moments. Figure 16 gives an overview of the coordinate systems.

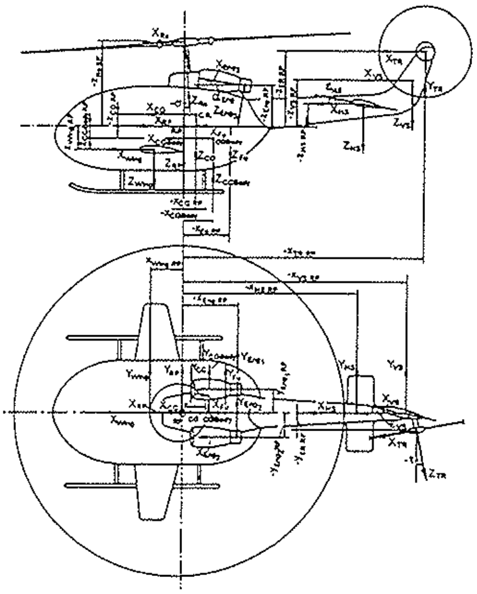

Figure 16: Body Axis Systems

In the model, each component of the helicopter except the rotor and fuselage is described analytically. Rotor and fuselage are described by polar curves. Furthermore, the rotor model includes the first flapping mode, which is calculated as a rigid blade motion around an articulated flapping hinge. The rotor rotation is considered as one degree of freedom for the autorotation. Additionally 2 Allison $250-C20B/C20C$ engines and an engine governor are modelled. It is possible to use different modes of the model for trim calculations, simulations, inverse simulations and stability investigations. In the trim mode, the necessary controls and the corresponding Euler angles ($\vartheta_0, \vartheta_C, \vartheta_S, \vartheta_{TR}, \Phi$ and Θ) are calculated for a specific flight condition, steady or accelerated. The six body degree of freedom equations in the area of the flight condition, which has to be trimmed, have to be linearized. Also, estimated data for the trim variables have to be given.
Subsequently, the effecting forces and moments of the different components of the helicopter model (see figure 16) are determined. Put into the transformed equations of motion,

$$\underline{T}_{Res.} = \begin{pmatrix} m \cdot \left(\dot{\underline{V}}_{Kf} + \underline{\Omega}_f \times \underline{V}_{Kf}\right) - \sum \underline{F}_f \\ \underline{\underline{I}}_f \cdot \dot{\underline{\Omega}}_f + \underline{\Omega}_f \times \left(\underline{\underline{I}}_f \cdot \underline{\Omega}_f\right) - \sum \underline{M}_f \end{pmatrix} \qquad (3)$$

the residual trim values $\underline{T}_{Res.}$ are calculated. If the residual trim values exceed a given maximum, a set of 36 derivatives $\underline{\underline{T}}$ will be created by systematic variation of all trim values. A better approximation for the control angles can be calculated by a linear extrapolation, according to a multi-dimensional "Newton Iteration". This procedure is repeated until the residual trim values remain under a given maximum. Then the required power P is determined.

For the simulation mode a "Runge-Kutta" integration algorithm is used. Here, for a given, comparably small, interval of time and defined controls $\underline{\vartheta}$, up to 36 partly joined non-linear differential equations, including the engine model, are integrated. Helicopters are unstable during the most flight conditions. Thus the application of a stabilization system, e.g. an attitude controller, is necessary for conducting controlled simulation flights. For details, see next chapter.

In case a series of several trim calculations have to be conducted, e.g. along a given flight path, this is defined as an inverse simulation, that means, for the particular given flight conditions, trim calculations are carried out one by the other, in order to gain the required control inputs as well as the resulting Euler angles. By an inverse simulation, the controls can be determined (pre-controls). They enable the helicopter model to conduct the requested flight path movements during the simulation.

Finally, the stability calculation might be mentioned, which allows the calculation of stability derivatives and Eigen-values along the linearized equation of motion.

4.5 Attitude Flight Path Controller

As described in chapter 4.3, it is possible to automate the approach by minimization of the deviations between determined and actual flight path by a control algorithm. For stationary horizontal flights, a comparably simple attitude flight path controller maybe sufficient. But a multi feedback controller should be more powerful. If permanent changes in flight direction and altitude are planned, the application of pre-controls is recommended, as has been introduced in the automatization concept. Consequently controls are known in advance and only deviations have to be adjusted. Due to the mostly unstable and non linear behaviour of the helicopter, for determination of pre-controls, an inverse simulation is suitable (see figure 15).

For control of attitude, primarily the Euler angles themselves are fed back. Additionally the body rates can be fed back for damping. The same applies for flight path control. Besides of the positions, the velocities can be considered here as well.

As shown in figure 17, the differences, that are formed between the Euler angles of the invers simulation $\underline{\Phi}_{De}$ and the present Euler angles $\underline{\Phi}$, are fed into a PI-controller. In addition to a mere feedback gain, the I-part is ment to decrease the control deviations. The differences between present and given body rates, multiplied with a feedback gain, are substracted from the integrated deviation of attitude. This way, fictive bank, pitch and yaw accelerations are determined. The flight path control is based on the same principle, that means, differences between given and present positions are fed into a PI-controller, from which the differences between the velocities, multiplied with a factor, are substracted. Fictive translation accelerations result. The characteristic of the controller consists of the fact, that, under consideration of an inertia matrix $\underline{I}$, and the derivative matrix $\underline{\underline{T}}$ which depends on the flight condition, these fictive accelerations can be transformed into additional control inputs $\Delta\underline{\vartheta}$. Subsequently, these are fed into the helicopter simulation model, together with the pre-controls of the inverse simulation.

By the described inertia matrix, which consists of the mass of the helicopter and the moments of inertia, multiplied with the fictive accelerations, forces and moments can be computed. With the inverse simulation or the trim calculation as described in chapter 4.4, so-called derivatives are calculated, which are the elements of the derivative matrix $\underline{\underline{T}}$. For a trimmed flight condition they describe a linearized correlation between moments or forces and control inputs of Euler angles (e.g. $\underline{\underline{T}}(3,1) = dF_z/d\vartheta_0$). By inverting the matrix, the forces and moments, which have been calculated as a result of acceleration, can be transformed into controls $\underline{\vartheta}$. The computation of the derivative matrix can be conducted during the simulation (online) as well as before the simulation by the inverse simulation. According to the introduced flight path (see figure 11), figure 18 shows a simulated approach. In this case, the parameters of control are fixed for the complete flight envelope. In addition to the results of the simulation, the results of the inverse simulation are presented. The approach picture shows, that differences between given and simulated path only occur during the last part of the final approach. High conformity between the simulated required power and the calculated required power can be noticed. Only during the last part of the flight, the simulated required power increases outstandingly and reaches the admissible maximum. The reason is, that the scope of the controller is beyond the area of this velocity. This can also be recognized by the fact, that in the final part the control curve diverges from the calculated control curve very much. This characteristic can be approved by skillful switching of the control parameters according to velocity.

Unfavourably, this adjustment of the controls produces good results only for specific flight situations. Further investigations therefore should concentrate on the development of an algorithm, which calculates optimized value control adjustments, depending on the particular flight condition (e.g. mass of the helicopter, velocity...)

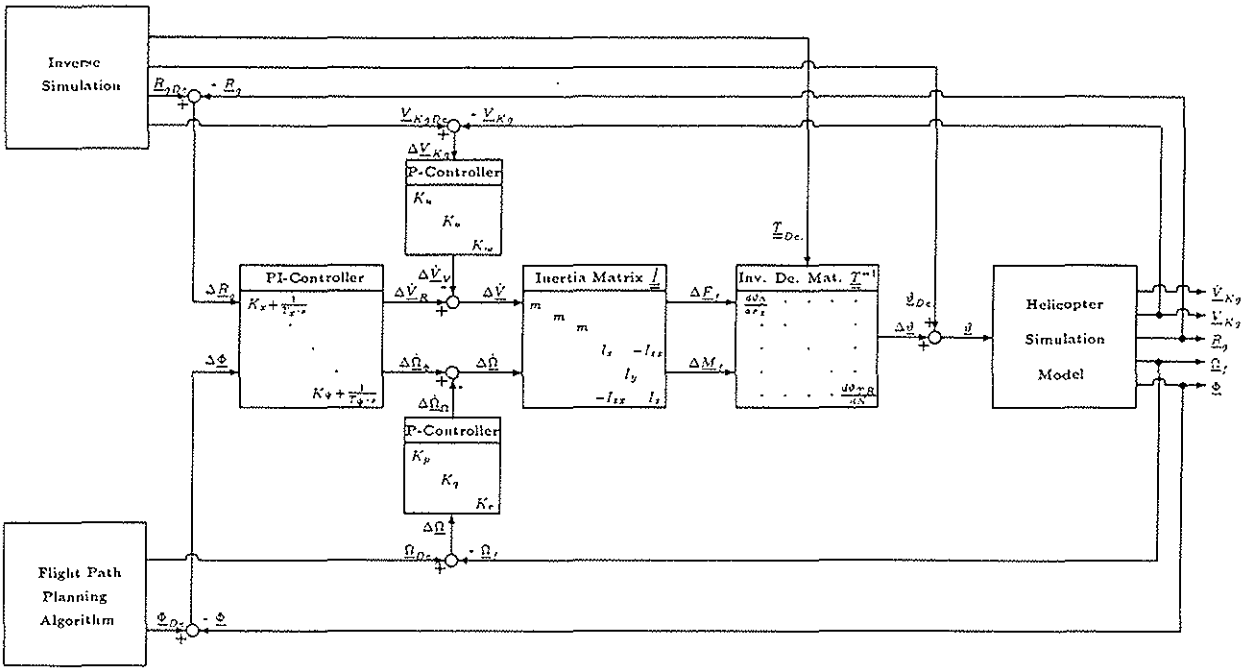

Figure 17: Control Algorithm

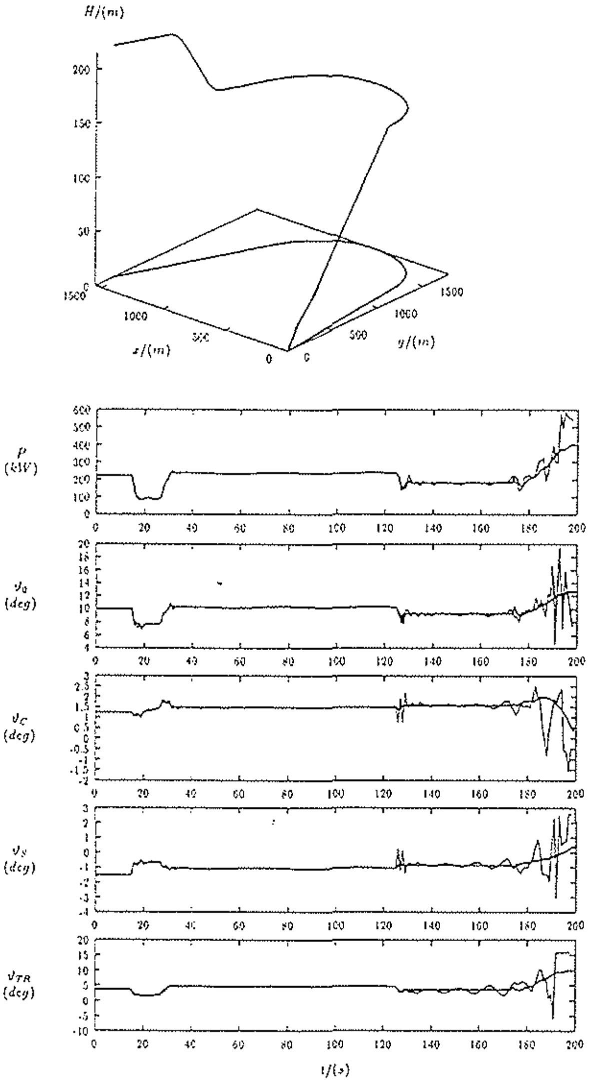

Figure 18: Simulated Approach

5. Conclusion

In order to reduce the pilot's workload and the safety risk especially in critical flight conditions, a procedure has been presented, that allows the pilot to plan a save approach during the flight. For the investigations, the steep approach was considered, because this approach procedure takes the typical characteristics of a helicopter into account, as the hover capability and the ability of vertical climb and descent. Based on a description of the limiting factors, such as vortex ring state, height-velocity diagram, etc., which restrict possible steep approaches, a flight path planning algorithm has been presented. It was found out, that a segmentation of an approach path is ingenious, in order to consider the margins in a better way. For the calculation of the segments, a six degree polynomial equation has been used. This avoids a flight path planning with continuous accelerations. Furthermore, total velocity oscillations are kept at a minimum, by using an optimization algorithm. Besides of the curves of the successive positions, the velocities and the acceleration, the necessary data for navigation by GPS and MLS systems was outlined.
Two possibilities have been discussed to guide a helicopter along a planned flight path. First, a display concept was shown, which indicates the present and the determined data of flight condition to the pilot. Second, a control algorithm for automated guidance of the helicopter until touch down was presented.

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