TWELFTH EUROPEAN ROTORCRAFT FORUM

Paper No. 45

AN ANALYTIC METHOD OF QUANTIFYING HELICOPTER AGILITY

D.G. Thomson

Department of Aeronautics and Fluid Mechanics

University of Glasgow

September 22-25, 1986

Garmisch-Partenkirchen

Federal Republic of Germany

Deutsche Gesellschaft fur Luft-und Raumfahrt e. V. (DGLR)

Godesberger Allee 70, D-5300 Bonn, F.R.G.

AN ANALYTIC METHOD OF QUANTIFYING HELICOPTER AGILITY

D.G. Thomson

Dept. of Aeronautics and Fluid Mechanics, Univ. of Glasgow.

Abstract

This paper outlines a method of measuring the Inherent Agility (i.e. the agility of the aircraft alone) of a helicopter configuration. The method is based on Inverse Solutions of the Equations of Motion and standard performance measurment techniques. Inverse solutions can be found for a helicopter performing a family of manoeuvres within specified limits. An Agility Performance Index is given for each manoeuve forming an agility surface covering this set of limits. An Agility Rating is then calculated as the volume under the surface. This agility rating corresponds to a single configuration over a single class of manoeuvre. Other configurations can then be tested over the same manoeuvres for comparison. The method is ilustrated by comparing the agility of three helicopter configurations; transport, battlefield and agile, over a series of standard manoeuvres.

1. Introduction

In recent years the role fulfilled by the military helicopter has grown from a purely utility and transportation vehicle to include ground attack and anti-armour duties. This puts the helicopter at ever increasing risk from ground-to-air fire, missile attack and air-to-air assault. In this hostile environment nap-of-the-earth (NOE) flight is used to improve survivability. This sort of flight lets the pilot use local terrain features to avoid detection and deny would-be aggressors the opportunity to lock-on any weapon guidance systems.

The term "agility" has been loosely used to describe the helicopter's overall performance under these conditions. It is a function of aircraft performance (maximum sustained load factor, turn rate, acceleration etc) but must also include handling qualities - good performance is useless unless pilots have the confidence to use it. A more formal definition of agility might be : *agility is the ease with which a helicopter can change its position and state with precision, speed and safety.*

Studies aimed at quantifying agility can be separated into two types, flight testing, including piloted simulation (Refs. 1,2), and analytic methods (Refs. 3,4). Flight tests (and simulation) have the disadvantage not only of high costs, but also of relating agility to subjective pilot opinion. Analytic methods are mainly used to study the effect of a particular configuration parameter on agility. The methods described by the authors of References 3,4, have therefore been developed to suit a particular application. These analysts have used kinematic helicopter mathematical models to study agility. The limitations of using kinematic models, as dicussed by Curtiss and Price (Ref. 5), are poor prediction of dynamic behaviour at low speed and, since these basic simulations do not include a rotor model, any consequent analysis of agility will not highlight any undesirably large control displacements during manoeuvring flight. This report outlines a general method of quantifying helicopter agility using a nonlinear dynamic model of a single main and tail rotor helicopter which is applicable over a wide range of unsteady flight conditions. By using this type of model the above limitations are avoided.

2. Overall and Inherent Agility

From the above definition it is clear that agility is a function of many parameters. The use of words such as "ease" and "safety" implies that agility must be a function of handling qualities and pilot workload hence involving control system performance. The word "precision" underlines the importance of control system design in helicopter agility. It is intuitive that "speed" is also of importance. Since pilot workload and handling qualities cannot be fully quantified by analytic methods it follows that agility also, cannot be fully quantified using analysis.

However, a distinction can be made between the overall agility of a helcopter system (taking into account performance, handling qualities, pilot workload, control system performance etc.) and the "inherent" or "configuration" agility of a particular helicopter design. Inherent agility can be considered as a function of a number of well defined configuration parameters (e.g. rotor stiffness, installed power etc.) and is therefore dependent only on design. Due to the importance of pilot workload and handling qualities overall agility can only be assessed by flight tests or piloted simulation (by using some sort of opinion scale for example). Inherent agility (of the configuration), however, may be quantified analytically. A value for the inherent agility of a helicopter can be given by studying its performance over a series of standard manoeuvres. These manoeuvres would represent typical tasks performed by the configuration under study. The combination of these tasks would constitute the helicopter's role. Configuration parameters can then be varied and their influence on the inherent agility of the configuration studied. This could provide a useful tool for the investigation of new configuration designs with respect to improvements in agility performance.

3. Relating Inherent Agility to Aircraft Dynamic Response

Basing a method of quantifying agility on a helicopter's performance while flying a series of standard manoeuvres, simplifies the definition of agility given in the Introduction. If, when comparing the inherent agility of various configurations, the change in position is the same for each, then the "position" and "precision" aspects of the above definition are accounted for. Inherent agility is then defined as the ease with which a helicopter can change its state, and is a function of the aircraft's dynamics. The time histories of the body axes velocities and fuselage attitude angles over a manoeuvre are a direct measure of a change of state. The corresponding time histories of control angles give an indication of the ease with which state has been changed. It can then be surmised that inherent agility, for a given configuration over a fixed manoeuvre, can be assessed by examination of its state and control time histories. A configuration with less control displacements and smaller changes in state variables over a fixed manoeuvre, has greater inherent agility. The influence and importance of each group of state and control variables is now discussed.

i) Attitude Angles

Large attitude displacements influence helicopter agility in NOE flight in the following ways.

a) Large roll displacements can cause height loss. This can be dangerous in low level flight. Roll displacements occur in longitudinal manoeuvres as well as in turns. During higher load factor longitudinal manoeuvres (e.g. rapid pull-ups) the cross coupling of pitch and roll with main rotor collective and cyclic pitch can cause large roll displacements. The resultant potential height loss has to be accounted for by increased collective pitch.

b) Rapid acceleration causes the nose of a helicopter to pitch down as the rotor disc tilts forward. This has two implications. Firstly the tail rotor (a major noise source) may appear above a covering tree line and secondly there is danger of an advancing blade ground strike. Similarly severe deceleration causes large nose up attitudes as the rotor disc tilts back. There is then the danger of tail rotor ground strike.

c) Extreme attitude changes (pitch, roll or yaw) can limit a pilot's vision as well as the loss of his visual cues and radar lock.

It is apparent that an agile configuration will perform a particular maneouvre with less attitude displacement then a less agile configuration.

ii) Translational Velocities

Translational velocities are of less importance in the assessment of inherent agility. The translational velocities are functions of the earth axes velocities (functions of flight path) and the attitude angles. Any analysis which accounts for attitude effects therefore also includes the influence of the translational velocities.

iii) Rotational Velocities

Large rotational velocities can cause loss of visual cues, disorientation, and high pitch velocity can cause dynamic stall. The effect of large rotational velocities should be accounted for in a study of agility.

iv) Control Displacements

The ease by which state has been changed is shown by the associated control time history (smaller control displacements show an easier change of state). The control time histories must then be important when quantifying inherent agility. Each control (like each state) has particular significance for a certain type of manoeuvre e.g. lateral cyclic is of more importance in turning manoeuvres than in longitudinal manoeuvres such as pop-ups. Main rotor collective pitch is of relevance in all manoeuvres due to the importance of altitude control in all NOE flight. Similarily, tail rotor collective is important in all manoeuvres as it is used to control direction.

4. An Analytic Method of Quantifying Helicopter Inherent Agility

The inherent agility of a helicopter can be quantified by defining a series of tasks and studying the control and state time histories needed to perform them. This could be achieved by flight simulation, but since the pilot would be unlikely to be able to perform the task (i.e. fly a precisely defined manoeuvre) with complete precision, and be able to repeat it, results may not be consistent. It is possible, however, to calculate control and state time histories for a given manoeuvre using an *inverse solution* of the equations of motion.

4.1 Inverse Solutions of the Equations of Motion

The standard type of forward solution of the equations of motion calculates an attitude and velocity time response from given control inputs. From the attitude and velocity response the flight path co-ordinates can be found (by transforming the body fixed axes velocities to an earth fixed system and then integrating w.r.t time). The inverse solution calculates the control input needed to fly a given manoeuvre. A computer program, HELINV, has been developed to produce this sort of solution (Ref.6). Manoeuvres are specified by (x,y,z) earth fixed axes co-ordinates, and a velocity distribution along this flight path (the earth axes system velocities and accelerations can then be found). Attitude angles, body fixed axes velocities and control angles are then calculated (using a non-linear mathematical model of a single main and tail rotor helicopter, Ref.7) for the manoeuvre. The manoeuvre can then be precisely repeated using a different configuration simply by altering configuration parameters in the mathematical model. The attitude, velocity and control time histories of various configurations flown over precisely the same manoeuvre can then be compared.

4.2 Agility Performance Index (API)

The performance of dynamic systems can be measured by a performance index (Ref. 8):

$$J = \int_0^t F(\mathbf{x},\mathbf{u})\, dt$$

where : J = performance index,
F = a cost function,
$\mathbf{x}$ = the state vector,
$\mathbf{u}$ = the control vector.

Improved performance is indicated by lower values of performance index and an optimum performance is observed when a minimum value is reached.

In flight mechanics the cost function is usually integrated over the manoeuvre time and is selected to suit a particular application (any undesirably large values of the state or control parameters being most heavily penalised). The most common form of cost function is a quadratic where the function is a sum of weighted squares of the state and control variables i.e. if a system has i states and j controls then;

$$F(x,u) = q_1.x_1^2 + ...+ q_i.x_i^2 + r_1.u_1^2 +..... + r_j.u_j^2$$

where : q_i = the weighting constant of state i,
r_j = the weighting constant of control j.

This sort of function heavily penalises large values of any state or control variable by squaring them. By careful selection of the weighting constants the more important variables can have greater influence over the value of the performance index than other less important variables. The values of q_i and r_j are dependent on the type of manoeuvre being performed i.e the cost function is weighted to suit particular tasks. The weighting constants for a turning (lateral) manoeuvre are different from those in a pop-up or hurdle-hop (longitudinal) manoeuvre.

The method used to award an agility performance index to a configuration flying a defined manoeuvre is fundamentally that described above with a few important changes. The agility performance index is defined as :

$$API = t'.\left\{ \sum_{i=1}^{n_s} q_i.\int_0^{t_m} \left[\frac{x_i(t) - x_{it}}{x_{im} - x_{it}} \right]^2 dt + \sum_{j=1}^{n_c} r_j.\int_0^{t_m} \left[\frac{u_j(t) - u_{jt}}{u_{jm} - u_{jt}} \right]^2 dt \right\}$$

where :
t_m = manoeuvre time,
t_{max} = maximum manoeuvre time (see below),
t' = t_m / t_{max}^2,
n_s = number of states,
q_i = weighting constant of state i,
$x_i(t)$ = time history of state i,
x_{it} = trim value of state i,
x_{im} = maximum allowable value of state i,
n_c = number of controls,
r_j = weighting constant of control j,
$u_j(t)$ = time history of control j,
u_{jt} = trim value of control j,
u_{jm} = limit of control j.

The cost function is based on ratios of instantaneous displacement to maximum allowable displacement of the states and controls. If a ratio of total value to maximum value had been used, then it would be impossible to compare the agility ratings of different configurations (due to possible differences in trim condition).

An extra term is added to account for the influence of engine performance. Agility can be directly related to the amount of excess power available and the rate at which it can be summoned for manoeuvring (see

Ref. 3). This influence can be accounted for by including the term :

$$API_{engine} = c_p . t' . \int_0^{t_m} \left[\frac{P(t) - P_t}{P_m - P_t} \right]^2 dt$$

where : API_{engine} = contribution to API by engine power,
$P(t)$ = the time history of engine power,
P_t = engine power in trim condition,
P_m = maximum engine power available.
c_p = weighting constant

The method of selecting the values of the weighting constants is simplified by setting the coefficients of less important states or controls to zero. Each of the remaining coefficients is varied in turn and the effect it has on the total API over a series of similar manoeuvres is noted. The relative size of each component of the total API (i.e. the contribution from each state and control variable) is examined (see Fig 2 for example). The series of coefficients which gives the contribution from each variable a value reflecting its relative importance in that particular sort of manoeuvre is chosen.

As the value of state (or control) displacement comes closer to the maximum allowable, the value of the ratio approaches unity. To make it easy to interpret agility indices it would seem desirable to keep its value between zero and one (the lower numbers indicating higher agility). This is achieved by having the sum of the coefficients equal to unity :

$$\sum_{i=1}^{n_s} q_i + \sum_{j=1}^{n_c} r_j + c_p = 1$$

Severity of manoeuvre can be accounted for by multiplying the cost function by manoeuvre time, t_m. This would allow configurations to be compared flying the same flight paths with a series of velocities (i.e. a series of similar manoeuvres). Flight paths flown at higher velocity (lower t_m) would be weighted to have lower API than the same flight path flown at a lower velocity (greater t_m). The units of API would then be seconds squared. If API values are being calculated for a series of similar manoeuvres (as is normal), then API can be normalised by division by the maximum manoeuvre time experienced squared (the manoeuvre flown most slowly in a variable velocity calculation or the manoeuvre flown over the greatest distance in a constant speed calculation). The maximum value of the integral before multiplication by t' is the manoeuvre time t_m. The maximum value of t' is $1/t_m$ (where $t_m = t_{max}$), therefore, the maximum value of API is unity. It should be noted that to reach a value anywhere close to one, the aircraft would have to fly the whole manoeuvre very slowly and very close to all its control and state limits. In practice API values rarely go above 0.1.

Using the performance function defined above, a value for an Agility Performance Index can be calculated for a helicopter flying a rigidly defined flight path at a given speed, the control and state time histories being calculated using an inverse solution of the helicopters equations of motion.

4.3 An example

To illustrate this method, agility performances indices have been calculated for a *pop-up* manoeuvre. The pop-up is a height change performed at a constant forward velocity and is used for obstacle clearance (see Fig. 4a.). The distance from the obstacle at the start of the manoeuvre (s_1) and the clearance height (h_1) are inputs to HELINV (along with flight velocity V_f) which then calculates the state and control time histories needed to fly this flight path (with entrance and exit in a trim condition). An agility performance index (API) can then be calculated for this single manoeuvre (this API corresponds *only* to the pop-up of distance s_1 and height h_1 flown at velocity V_f). The same flight path can be "flown" at a series of velocities and an API calculated for each of them. Similarly, the distance to the obstacle may be varied to give geometrically different flight paths to be flown at a fixed velocity. The same series of manoeuvres can then be flown for different configurations and their API's compared.

In this example, configuration data (see Table 1) for two different classes of conventional helicopter, a transport and a battlefield aircraft, have been used in the mathematical model. The transport configuration has an articulated rotor with a small offset flapping hinge whilst the battlefield helicopter has a rigid flapwise stiff rotor. The coefficients of the performance function are given in Table 2, the maximum control values in Table 3 and the maximum allowable values for the states in Table 4.

i) Agility Performance Index vs. Flight Velocity

Here a single flight path (s_1 = 300m , h_1 = 25m) is flown over a series of velocities (60-100 knots). Plots of API against velocity for this manoeuvre using the two sets of data are shown in Fig 1a. Figure 2 shows the contributions from each state and control variable. As would be expected, Fig. 1a shows that the battlefield configuration is more agile (lower API) than the transport over this manoeuvre.

ii) Agility Performance Index vs. Distance to Obstacle

Here the distance to the obstacle was varied between 250 and 350m and the resulting flight paths were all flown at 80 knots. The API is plotted against distance in Figure 1b. Again, the battlefield configuration is shown to be more agile than the transport.

These plots show increased agility (lower API) at greater distances and lower speeds. This is because the greater the distance from the obstacle, or the lower the speed, the less severe the manoeuvre, hence the lower the control,attitude and velocity displacements. The curves are of exponential shape because as the distance increases, or velocity decreases, so does the manoeuvre time hence offsetting the lower contributions from control and attitude displacements.

4.4 Agility Ratings

It is shown above that API's can be calculated for a configuration either over a series of velocities, or a series of similar flight paths.

This gives an indication of the agility performance of the configuration over a series of similar manoeuvres, of varying severity. An overall indication of the configuration's agility for a single class of manoeuvre can be found by consideration of the API values calculated over a series of velocities *and* a series of similar flight paths. By setting fixed upper and lower limits of velocity and flight path parameter for the calculation, the manoeuvres are then standardised. The inherent agility of any number of configurations can now be compared by calculating their "Agility Rating" for these manoeuvres.

Plotting the API's would produce a 3-d surface (such as Fig. 3), with velocity and a flight path parameter as x and y axes, and with API as the z-axis. This "agility surface" would represent the inherent agility of a configuration over a single class of manoeuvre. Greater agility is achieved when the suface is closer to the x-y plane (i.e. lower API values). In other words, the less the volume under the surface then the greater is the agility. The agility rating (AR) of the configuration is taken to be the volume under this surface.

Agility rating is defined as :

$$AR = \int_{s_{min}}^{s_{max}} \int_{V_{fmin}}^{V_{fmax}} API \quad ds \, dV_f$$

where : AR = Agility rating,
s_{max}, s_{min} = Limits of a flight path variable
V_{fmax}, V_{fmin} = Limits of flight velocity
API = Agility performance index.

The units of Agility Rating are m^2/s. Since agility ratings are only used for comparisons these units are of no real significance.

This method can be illustrated by considering the pop-up manoeuvre described above. The surface shown in Figure 3 is made up of API values for a series of pop-up manoeuvres with velocity varied between 60 and 100 knots and the distance to a 25m obstacle varied between 250 and 350 metres. Data for the battlefield configuration has been used. The agility rating given by the volume under this surface is 0.717. The same series of manoeuvres has been performed using the data for the transport configuration and its *pop-up agility rating* is calculated to be 1.029. The lower value calculated for the battlefield helicopter shows it has greater agility than the transport configuration over a complete series of pop-up manoeuvres.

5. A Comparison of the Inherent Agility of Three Configurations

The method of assessing inherent agility described in this document is at its most useful in configuration studies. To illustrate its use a series of standard flight paths has been defined, and agility ratings for each has been calculated for three configurations - the transport and battlefield helicopters described above, and an "Agile Battlefield Helicopter" (ABH). The leading configuration data for each is given in Table 1.

5.1 The Agile Battlefield Helicopter

The ABH configuration is based on the standard battlefield helicopter with certain configuration parameters altered to make it more agile. Configuration parameters such as c.g. position, tail plane area, aircraft mass etc. can all influence inherent agility (since they all influence the attitude and hence control displacements in unsteady flight). The following factors have been modified in the ABH aircraft in an attempt to make it more agile than its original battlefield configuration.

i) Installed Power

A helicopter has four sources of power : installed power (engine), rotor inertia (rotational kinetic energy), altitude loss (potential energy), airspeed loss (kinetic energy). In order for the helicopter to manoeuvre it must gain energy from one of these sources. In NOE flight it is not practical to lose height or airspeed thus engine power is used to manoeuvre. Since agility is directly related to excess power and the speed at which it may be summoned, good engine response and performance are desirable. In particular a responsive engine (short run-up and shut down times) are important in acceleration and decceleration manoeuvres. An analysis of engine power influence on agility is given by Merkley (Ref. 3). The maximum output of the engine has been increased from 1670kw to 2500kw without any increase in weight.

ii) Rotor Flapping Stiffness and Blade Inertia

The control moment produced by a helicopter rotor is made up of two parts : a thrust moment due to rotor tilt and a Coriolis moment due to the flapping hinge offset. The magnitude of the Coriolis moment depends on the flapping stiffness of the rotor which in turn is a function of blade flapping inertia and effective hinge offset. A helicopter possessing a greater rotor stiffness (and hence larger Coriolis moment) will require a smaller thrust vector tilt to produce the same control power as a helicopter with a less stiff rotor. As pitch attitude is directly related to disc tilt, increased rotor stiffness gives lower pitch attitudes. Tomlinson and Padfield have shown the importance to agility of these rotor parameters (Ref. 1). The rotor stiffness has been increased from 166 to 250 kNm/rad. It should be noted that this change has increased the effective flapping hinge offset from 0.161 to 0.197. This can cause problems in control system design since effective offset effects the dynamic behaviour of the rotor (in particular the lag between pitching and flapping).

iii) Rotor Solidity

Rotor solidity can be increased by adding extra blades. The blades of the high solidity rotor require lower pitch displacements to produce the same lift as a similar rotor with fewer blades. The drag of each individual blade is reduced although the sum of the drag of all the blades may have increased. Since the high solidity rotor will require smaller control displacements inherent agility should be improved. The rotor of the ABH has been given one extra blade.

iv) Tailplane Area

It has been shown, using the method described in this paper, that the agility of the battlefield configuration can be improved by decreasing its tailplane area (Ref. 9). The improvement is most noticeable in pitching manoeuvres such as pop-up's etc. The download on the tail is helpful in the pull-up section of the manoeuvre whilst it is a hinderance in the push-over section. Results have shown the optimum value for tail area to be about half its present size. This represents the tailplane area which gives the best compromise between the advantageous tail download in pull-ups and adverse download in push-overs.

5.2 Definition of the Standardised Flight Paths

Helicopter inherent agility is related to manoeuvre type and therefore an agility rating is assigned to a helicopter for a particular class of manoeuvre. An assessment of total inherent agility must include agility ratings for a series of manoeuvres or tasks representing the helicopter's role. For this example, the series of manoeuvres for NOE operations is :

a) Pop-up : height change h_1= 25m over a distance s_1 at constant forward velocity (Fig. 4a).

Velocity Limits : $60 \leqslant V \leqslant 100$ knots
Distance Limits : $250 \leqslant s_1 \leqslant 350$ m

b) Hurdle-Hop : obstacle clearance of height h_1=25m with return to original height at distance s_2 with constant forward speed (Fig. 4b).

Velocity Limits : $60 \leqslant V \leqslant 100$ knots
Distance Limits : $500 \leqslant s_2 \leqslant 600$ m

c) Constant Height Turn : right hand 90° of radius R, turn at constant height and velocity. The turn is made of transient entry and exit components with a circular main section.

Velocity Limits : $40 \leqslant V \leqslant 80$ knots
Radius Limits : $200 \leqslant R \leqslant 300$ m

d) Acceleration : Velocity change from V_1 to 60 knots over a distance s_1 at constant height.

Velocity Limits : $20 \leqslant V_1 \leqslant 40$ knots
Distance Limits : $100 \leqslant s_1 \leqslant 200$ m

e) Deceleration : Velocity change from V_1 to 15 knots over a distance s_1 at constant height.

Velocity Limits : $30 \leqslant V_1 \leqslant 50$ knots
Distance Limits : $150 \leqslant s_1 \leqslant 200$ m

f) Climbing Turn : Right handed 90° turn of radius R to a height of 25m at a constant velocity V (Fig. 4c).

Velocity Limits : $40 \leqslant V \leqslant 80$ knots
Radius Limits : $200 \leqslant R \leqslant 300$ m

The above flight paths and their limits have been chosen to represent as far as is possible, realistic manoeuvres performed by battlefield helicopters in NOE operations. The severity of manoeuvre is limited by the range of validity of the mathematical model and the accuracy of the inverse method (Refs. 7 and 6). It is assumed that all manoeuvres are performed with zero sideslip. If a full measure of inherent agility was to be found then other manoeuvres would be included (i.e. bob-up - height change in the hover and the wing-over - 180° turn around with height change etc.).

5.3 Selection of Weighting Constants

The values chosen for the weighting constants depend on manoeuvre type. Table 2 gives the values of the constants for the four types of manoeuvre. The pop-up and hurdle-hop are classed as the same type of manoeuvre since they both involve altitude variations at constant forward speed. The weighting constants for the translational velocities (u,v,w), the yaw angle ψ, and its rate r, have all been set to zero since they are of little importance in this study. Power is significant in all types of manoeuvres and its weighting constant is given a high value in each. The choice of constants for each type of manoeuvre is now discussed.

i) Pop-up/Hurdle-hop

The variables associated with pitching are most heavily weighted in these longitudinal manoeuvres since low values of pitch attitude and velocity are important for greater agility. Roll attitude is also given a weighting constant since small angles are experienced in pitching flight due to coupling. Roll rates in this type of manoeuvre are small therefore the corresponding weighting constant is made zero. Values are given to all the control angle constants with collective and longitudinal cyclic being the most dominant (see Fig. 2).

ii) Level Turn

The roll angle adopted by a helicopter in a turn is a fuction mainly of its turn rate, the dynamics of the aircraft having little influence. This means that for a given turn and velocity the roll angle will be similar for all helicopters. The weighting constant for this variable is therefore set to zero. Roll rate is weighted since this is a more important variable in agility studies. Again, all controls are weighted but with lateral cyclic the most influential.

iii) Speed Change

The weighting coefficients in these manoeuvres are chosen for similar reasons as those for the longitudinal manoeuvres, variables associated with pitching having a higher rating. Main rotor longitudinal cyclic is given has the largest coefficient since it gives an indication of the disc tilt required to produce the commanded acceleration (or deceleration). The rate at which the thrust vector can be tilted is an important factor in agility during speed changes.

iv) Climbing Turn

Since this is a three dimensional manoeuvre the weighting coefficients are more evenly divided, the roll constant is still set to zero for the same reason as the level turn.

5.4 Choice of Maximum Values

The control limits for the three configurations are given in Table 3 and the maximum values for the state variables in Table 4. The control limits represent the maximum value at the control surface. The maximum values for the state variables should be chosen either for safety or for pilot comfort. For example, large attitude rates may cause the pilot to lose visual cues or be disorientated whilst large pitch angles can cause problems with ground clearance for the rotor blades. Due to limitations in the mathematical model and the inverse algorithm, some of the limits presented in Table 4 may be unrealistic, e.g. a limit of 20° has been put on pitch attitude for speed change manoeuvres whereas in reality values far exceeding this are common.

5.5 Results

Agility ratings for all three configurations for the seven manoeuvres described above are presented in Table 5. For each manoeuvre, and each configuration, inverse solutions have been performed for a series of flight paths and velocities within the ranges given in 5.2. An Agility Performance Index is awarded to the configuration for each of these flight path/velocity combinations and an Agility Rating calculated as the volume under the surface of API values.

Intuitively, the transport configuration should be less agile than the other two. The large gap between the agility ratings for the transport configuration, and those for the battlefield and ABH configurations, confirms this. The size of the difference is most likely due to the different types of rotor. The gap between the battlefield and ABH configurations is largest in the longitudinal and speed change manoeuvres. In these manoeuvres the ABH configuration, with its stiffer rotor, has the advantage of being able to produce the same control moment with a smaller disc tilt (and therefore lower fuselage pitch displacement).

As would be expected the ABH configuration is the most agile. The contributions made to its increased agility, over the battlefield configration, were assessed by making each modification to the battlefield helicopter in turn, and noting the difference in agility rating for the series of manoeuvres. This study showed that the largest contribution came from increasing the installed power, the changes made to the rotor and tailplane being of secondary importance.

6. Conclusions

A method of assessing helicopter inherent agility has been developed using inverse solutions of the equations of motion. The success of the method depends largely on the reliability and accuracy of the inverse solution. To give a complete estimate of agility, the inverse algorithm must be able to predict control and state responses of a configuration over a wide range of realistic manoeuvres. The inverse algorithm must also give accurate and valid solutions for the most severe manoeuvres. At present the inverse method suffers from some limitations but improvements are being made to the algorithm to allow a wider range of unsteady flight states to be simulated. Another major drawback is having to chose appropriate values for the weighting constants in the agility performance function. A precise stategy for their choice should be produced. Similarly, the types of manoeuvre and their limits must be standardised before this method can be used more widely. The example given in this report does show the potential of this method in configurational studies of helicopter agility.

7. Notation

p,q,r	Rotational velocities about the body fixed axes
u,v,w	Translational " " along " " " " " " "

θ	(THT)	Fuselage pitch attitude
ϕ	(PHI)	" " roll " "
ψ	(PSI)	" " yaw " "

θ_0	(THTO)	Main rotor collective pitch
θ_{1s}	(THT1S)	" " " " longitudinal cyclic " "
θ_{1c}	(THT1C)	" " " " lateral cyclic " "
θ_{0tr}	(THOTR)	Tail " " collective " "

8. References

1. R.N. Tomlinson, G.D. Padfield — Piloted Simulation Studies of Helicopter Agility. Vertica Vol. 4 1979.

2. P. Brotherhood, M.T. Charlton — An Assessment of Helicopter Turning Performance During Nap-of-Earth Flight. RAE Tech. Memo FS(B) 534, Jan. 1984.

3. D.J. Merkley — An Analytic Investigation of the Effects of Increased Installed Horsepower on Helicopter Agility in the Nap-of-the-Earth Enviroment. USAAMRDL-TN-21, December 1974.

4. Lt P.J. Legge, RN, P.W. Fortescue, P. Taylor. — Preliminary Investigation into the Addition of Auxiliary Longitudinal Thrust on Helicopter Agility. Paper Presented at the 7th European Rotorcraft Forum, September 1981.

5. H.C. Curtiss, Jr., G. Price — Studies of Rotorcraft Agility and Manoeuvrability. Paper Presented at the 10th European Rotorcraft Forum, August 1984

6. D.G. Thomson — Helicopter Control Generation By Inverse Solution of the Equations of Motion. Univ. of Glasgow, Dept. of Aeronautics, Report No. 8502, October 1985.

7. G.D. Padfield — A Theoretical Model of Helicopter Flight Mechanics for Application to Piloted Simulation. RAE, TR 81048, April 1981.

8. R.J. Richards — An Introduction to Dynamics and Control. Longman, 1979, Section 4.

9. D.G. Thomson — An Analytic Method of Quantifying Helicopter Agility Using Inverse Solutions of the Equations of Motion. Ph.D Thesis, In Preparation.

Acknowledgements

The author wishes to thank Mr R. Bradley for his assistance in the preperation of this document. Thanks are also due to Dr G.D. Padfield and Dr S.S. Houston of Flight System Division, RAE Bedford for their assistance and support. This work is funded under an S.E.R.C. CASE Award with the Royal Aircraft Establishment F.S.(B) as external collaborating body.

Parameter	Helicopter Type		
	Transport	Battlefield	ABH
Mass (kg)	6000	4300	4300
Rotor Radius (m)	7.5	6.4	6.4
No. of Blades	4	4	5
Rotor Stiffness (kNm/rad)	48	166	250
Blade Flapping Inertia (kgm^2)	1300	680	800
Effective Hinge Offset	0.048	0.161	0.197
Maximum Power (kw)	2615	1670	2500
Rotor Solidity	0.0906	0.0778	0.0973
Tailplane Area (m^2)	1.35	1.2	0.6

Table 1 : Configuration Data

State or Control	Manoeuvre			
	Pop-up/Hurdle-hop	Level Turn	Accel./Decel	Climbing Turn
p	0.0	0.075	0.0	0.15
q	0.35	0.0	0.1	0.15
θ	0.2	0.08	0.01	0.15
ϕ	0.01	0.0	0.1	0.0
θ_0	0.02	0.15	0.095	0.1
θ_{1s}	0.32	0.3	0.3	0.15
θ_{1c}	0.05	0.12	0.15	0.1
θ_{otr}	0.02	0.05	0.15	0.1
Power	0.03	0.225	0.095	0.1

Coefficients for u,v,w,r,ψ zero.

Table 2 : Coefficients for Performance Function

Control	Transport	Battlefield / ABH
Main Rotor Collective	6 , 18	-5 , 20.3
Longitudinal Cyclic	-12.25 , 16.25	-15.7 , 7.5
Lateral Cyclic	3.5 , 6.5	-7.5 , 7.5
Tail Rotor Collective	-28 , 12	-8.5 , 33.5

Table 3 : Control Limits (in degrees)

State	Manoeuvre			
	Pop-up/Hurdle-hop	Level Turn	Accel/Decel	Climbing Turn
p (deg/s)	-------------	100	--------	100
q (deg/s)	50	--------	50	50
θ (deg)	20	5	20	20
φ (deg)	5	--------	5	---------

Table 4 : Maximum Allowable Values for States

Manoeuvre	Configuration		
	Transport	Battlefield	ABH
Pop-up	1.029	0.717	0.558
Hurdle-Hop	0.686	0.436	0.316
Level Turn	0.425	0.125	0.117
Acceleration	4.450	2.018	1.643
Deceleration	0.275	0.148	0.126
Climbing Turn	1.007	0.411	0.319

Table 5 : Agility Ratings

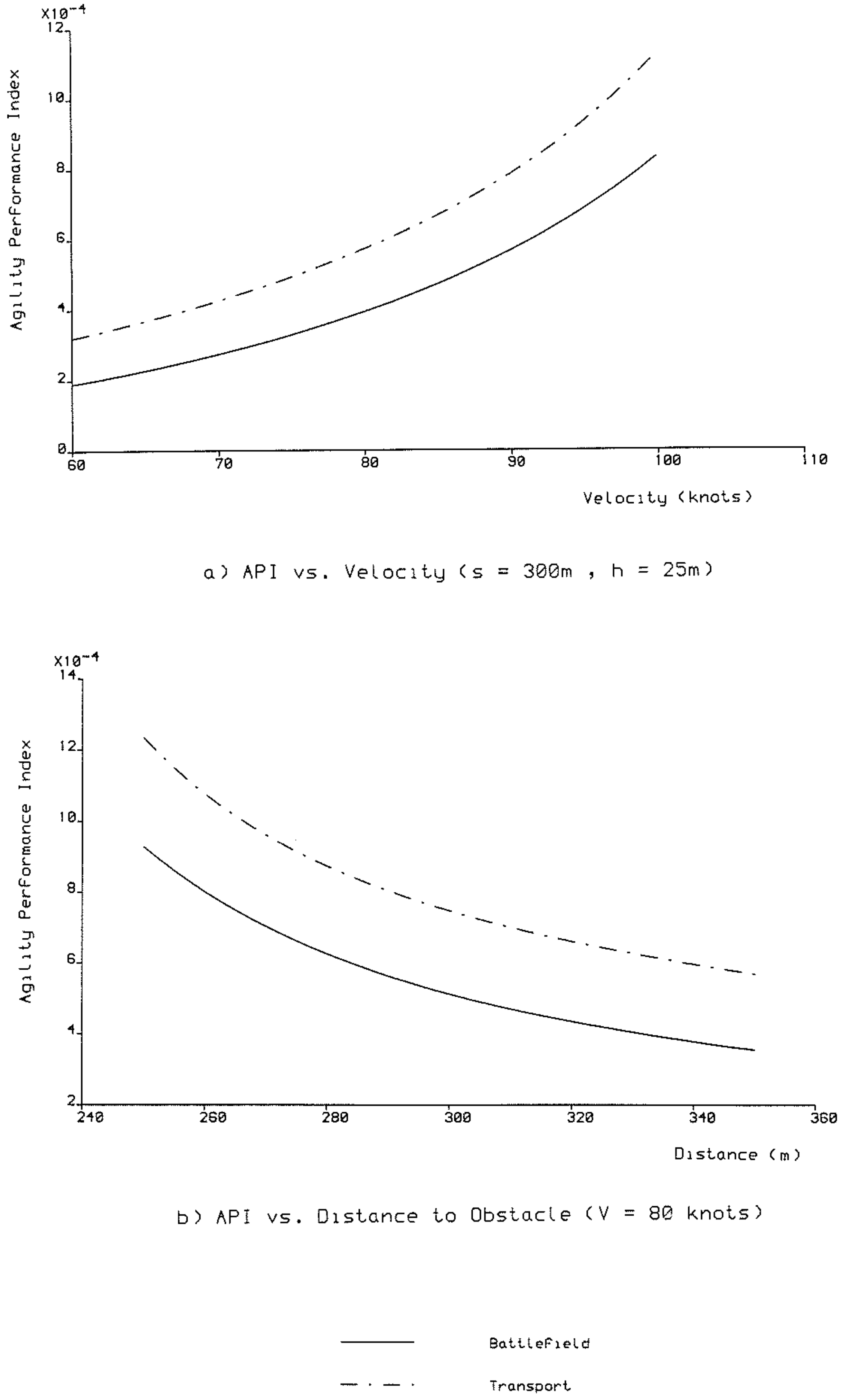


Figure 1 : Agility Performance Index Plots For the Pop-up Manoeuvre

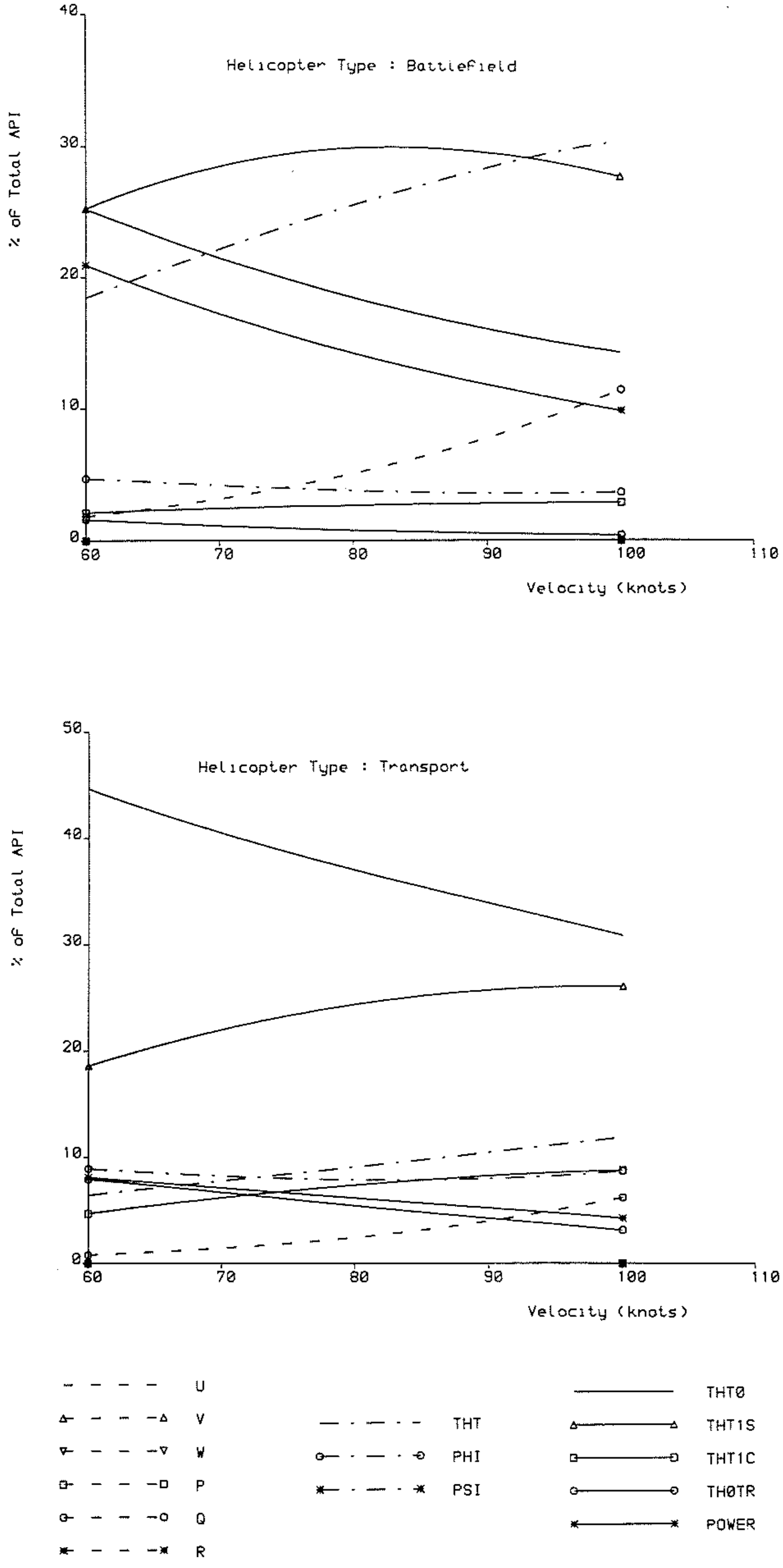


Figure 2 : Components of Agility Performance Index for the Pop-up Manoeuvre

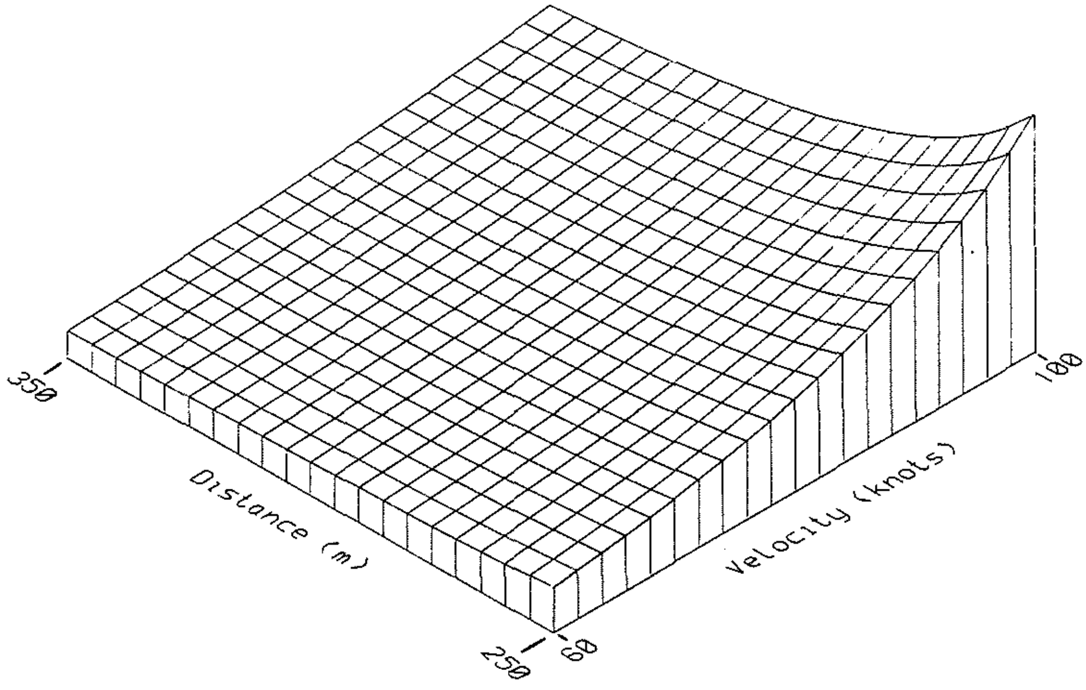
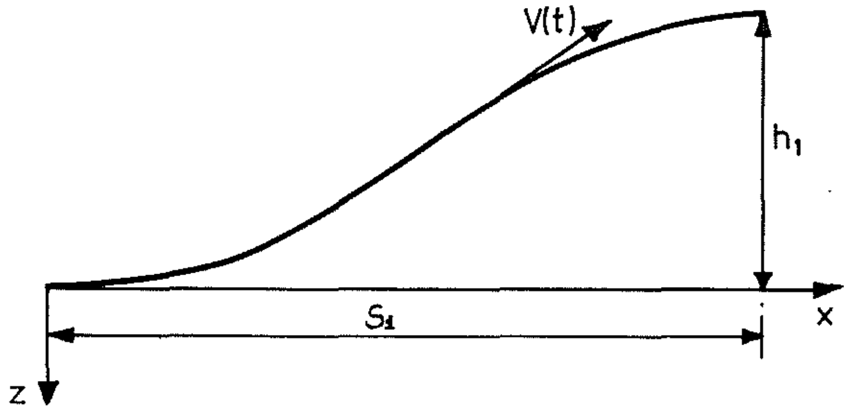
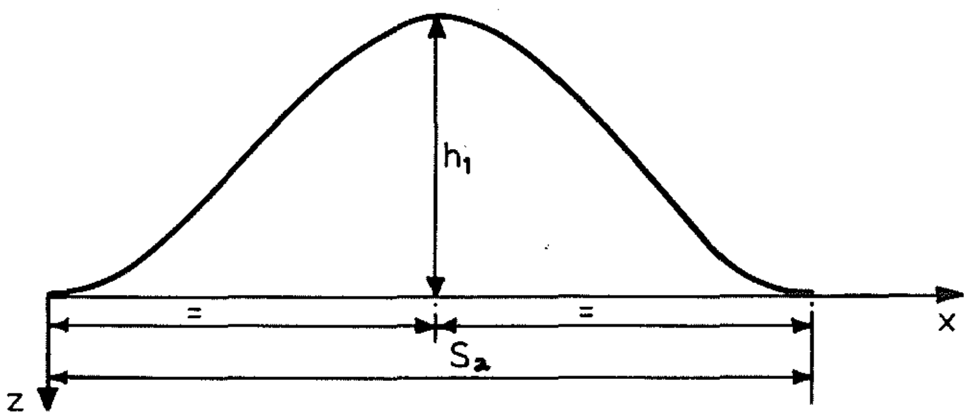


Figure 3 : Agility Surface For Pop-up Manoeuvre

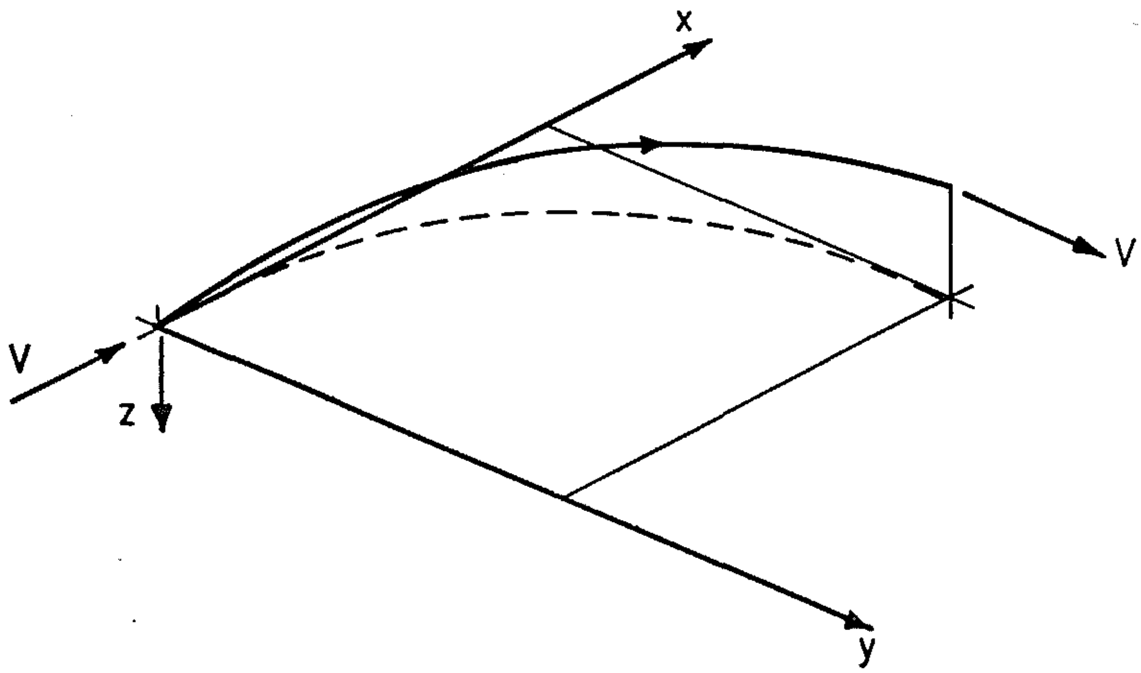


a) The Pop-up Manoeuvre



b) The Hurdle-Hop Manoeuvre

Figure 4 : Some Standard Manoeuvres



c) The Climbing Turn Manoeuvre

Figure : 4 (Continued)