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The Development and Potential of Inverse Simulation for the Quantitative Assessment of Helicopter Handling Qualities

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Abstract

In this paper it is proposed that inverse simulation can make a positive contribution to the study of handling qualities. It is shown that mathematical descriptions of the MTEs defined in ADS-33C may be used to drive an inverse simulation thereby generating, from an appropriate mathematical model, the controls and states of a subject helicopter flying it. By presenting the results of such simulations it is shown that, in the context of inverse simulation, the attitude quickness parameters given in ADS-33C are independent of vehicle configuration. An alternative quickness parameter, associated with the control displacements required to fly the MTE is proposed, and some preliminary results are presented.

Nomenclature

API	Agility Performance Index
n_s, n_c	number of states and controls in API function
p, q, r	components of aircraft angular velocity in body axes
q_i, r_j	weighting constants for API
t_a	time to reach maximum acceleration in Rapid Sidestep MTE
t_d	time to reach maximum deceleration in Rapid Sidestep MTE
t_l	time in acceleration phase of Rapid Sidestep MTE
t_m	time taken to complete manoeuvre
u	control vector
u, v, w	components of aircraft velocity in body axes
V_f	airspeed
V_{max}	maximum airspeed reached in manoeuvre
$\dot{V}_{max}$	maximum acceleration during Rapid Sidestep MTE
$\dot{V}_{min}$	maximum deceleration during Rapid Sidestep MTE
x	state vector
y	output vector
$\dot{\chi}$	turn rate
ϕ, θ, ψ	aircraft attitude angles
θ_0	main rotor collective pitch angle
θ_{1s}, θ_{1c}	longitudinal and lateral cyclic pitch angles
$\theta_{0_{tr}}$	tailrotor collective pitch angle

1. Introduction

The need to assess the overall handling qualities of a helicopter by its performance and handling characteristics in a range of typical manoeuvres has been recognised by the authors of the U.S. Handling Qualities for Military Rotorcraft [1]. As part of demonstrating compliance with these requirements, a set of standard manoeuvres, or Mission Task Elements (MTEs) has been defined and criteria for performance and handling have been specified. In addition, the authors of this document have indicated that mathematical models are an appropriate basis for evaluation and analysis at the design stage. By its nature, inverse simulation encapsulates this combination of precisely defined manoeuvre and mathematical modelling. With inverse simulation, a mathematical representation of a MTE is used to drive a helicopter model in such a way that the vehicle's response and control displacements may be derived. In effect, a flight trial of the modelled helicopter flying a given MTE is performed, and the information collected from such simulations is as extensive as that recorded in a real trial. It follows that inverse simulation has the potential of being a useful validation tool for manoeuvring flight, [2], but the question arises as to whether the data collected can be analysed for the evaluation of handling qualities in the same manner as that from a flight test of the real aircraft. The two conditions:

i) The mathematical model of the helicopter must have a suitably high level of fidelity for the flight conditions encountered in the MTE;

ii) The mathematical model of the MTE must be representative, in some sense, of the real manoeuvre;

might reasonably be considered as necessary before a positive response can be made but whether these conditions are, in addition, sufficient is the subject of current research at Glasgow.

This paper describes the rationale behind the belief that inverse simulation has an important contribution to make in the evaluation of helicopter handling qualities. A number initial studies have been performed using the helicopter inverse simulation package Helinv, [3] and some preliminary results will be presented in later sections of this paper. In the section that follows some of the main features of inverse simulation and manoeuvre description are discussed. Next, in section 3, a number of exploratory studies are described. These studies involve three methods of extracting information from the results of inverse simulation: performance comparisons, handling qualities indices and quickness parameters. It will be argued that the first two methods are likely to be limited both in their potential and in their applicability, while the quickness parameter approach shows particular promise since it goes some way towards resolving the question of the sufficiency of the two conditions listed above.

2. Inverse Simulation of Mission Task Elements

It is convenient to begin the discussion relating to the assessment of handling qualities by clarifying the term 'inverse simulation' as it is employed in relation to the work at Glasgow. Other authors [4, 5] have different interpretations related to the context in which it is employed. Also, the technique is not universally familiar, so that the feasibility of deriving a unique set of control responses from a given flight path is often questioned. The general problem is a good starting point for the discussion.

2.1 Inverse Simulation - The General Problem

The simulation exercise of calculating a system's response to a particular sequence of control inputs is well known. It is conveniently expressed as the initial value problem:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u}); \quad \mathbf{x}(0) = \mathbf{x}_0 \tag{1}$$

$$\mathbf{y} = \mathbf{g}(\mathbf{x}) \tag{2}$$

where $\mathbf{x}$ is the state vector of the system and $\mathbf{u}$ is the control vector. Equation (1) is a statement of the mathematical model which describes the time-evolution of the state vector in response to an imposed time history for the control vector $\mathbf{u}$. The output equation, (2), is a statement of how the observed output vector $\mathbf{y}$ is obtained from the state vector.

Inverse simulation is so called because, from a pre-determined output vector $\mathbf{y}$ it calculates the control time-histories required to produce $\mathbf{y}$. Consequently, equations (1) and (2) are used in an implicit manner and, just as conventional simulation attaches importance to careful selection of the input $\mathbf{u}$, inverse simulation places emphasis on the careful definition of the required output $\mathbf{y}$.

2.2 Application to the Helicopter

In the helicopter application discussed here, the state vector is $\mathbf{x} = [u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi]^T$ and the control vector is $\mathbf{u} = [\theta_0\ \theta_{1s}\ \theta_{1c}\ \theta_{0_{tr}}]^T$. The focus of the work at Glasgow is on manoeuvres that are defined in terms of motion relative to an Earth-fixed frame of reference so that the output equation is the transformation of the body-fixed velocity components into Earth axes. For a unique solution to the inverse problem it is necessary to add a further output, a prescribed heading or sideslip profile being the most appropriate choice. The four scalar constraints - three velocity components and one attitude angle - serve to define uniquely the four control axes of the helicopter.

The sophistication of the modelling implied by the form of $\mathbf{f}$ in equation (1) is of central importance since the more complex the basic formulation, the more difficult it is to cast into a useful inverse form. The mathematical model used for this early work was Helistab [6]; Thomson and Bradley [3] have described a method for the unique solution of the inverse problem in this case. Current work at Glasgow University employs an enhanced model, Helicopter Generic Simulation (HGS), [7] which is accessed by the inverse algorithm, Helinv. The main features of HGS include a multiblade description of main rotor flapping, dynamic inflow, an engine model, and look-up tables for fuselage aerodynamic forces and moments. The host package, Helinv, incorporates several sets of pre-programmed manoeuvre descriptions which are required as system outputs from the simulation. In fact, the manoeuvres are essentially the input into the simulation and much of the value of Helinv lies in the scope and validity of the library of manoeuvre descriptions which have been accumulated. They include those relating to Nap of the Earth [8], Air-to-air Combat, Off-shore Operations [9], and of particular interest in this study, Mission Task Elements [10]. There is also a facility for accessing flight test data. Some examples of these manoeuvres are discussed in the following section below.

2.3 Mathematical Representation of Mission Task Elements for Use with Inverse Simulation

The need for careful attention to the modelling of the required output - here the flight-path - has been emphasised in 2.1 above. It might appear, at first sight, that for a given general description of a manoeuvre that there is a wide choice of possible definitions of the trajectory. This turns out not to be the case, however, because given such freedom, the obvious starting point is to choose the simplest option but, as is discussed below, the simplest option appears to omit key qualitative features and, subsequently, in section 3 it will be argued that this view can be confirmed by applying quantitative criteria to the manoeuvre definition. However, the simplest case is a useful entry point for the discussion.

2.3.1 Mathematical Representation of Manoeuvres Using Global Polynomial Functions

Part of the early work on inverse simulation at Glasgow involved creating a library of models on helicopter nap-of-the-earth manoeuvres. The approach used was to fit simple polynomial functions to the known profiles of the primary manoeuvre parameters; velocity, acceleration, turn rate, or simply the helicopter's position. For example, an acceleration from a trimmed hover state to some maximum velocity, followed by a deceleration back to the hover is one of the most basic forms of manoeuvre which might be encountered. Consequently the approach used to derive a model of it is fairly simple. As the vehicle is to be in a trimmed hover state at both entry and exit, implying both zero velocity and acceleration at these points, and applying the condition that the maximum velocity, V_{max} should be reached half way through the manoeuvre, it is possible to fit a sixth order polynomial to these conditions to give the velocity profile

$$V(t) = V_{max}\left[-64\left(\frac{t}{t_m}\right)^6 + 192\left(\frac{t}{t_m}\right)^5 - 192\left(\frac{t}{t_m}\right)^4 + 64\left(\frac{t}{t_m}\right)^3\right] \quad (3)$$

where t_m is the time taken to complete the manoeuvre.

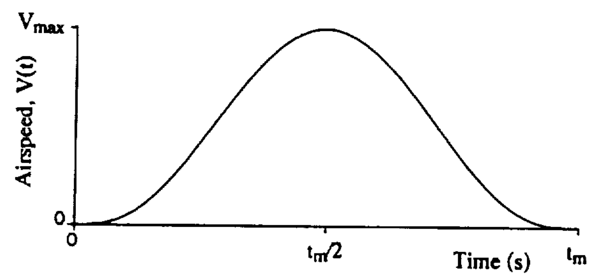
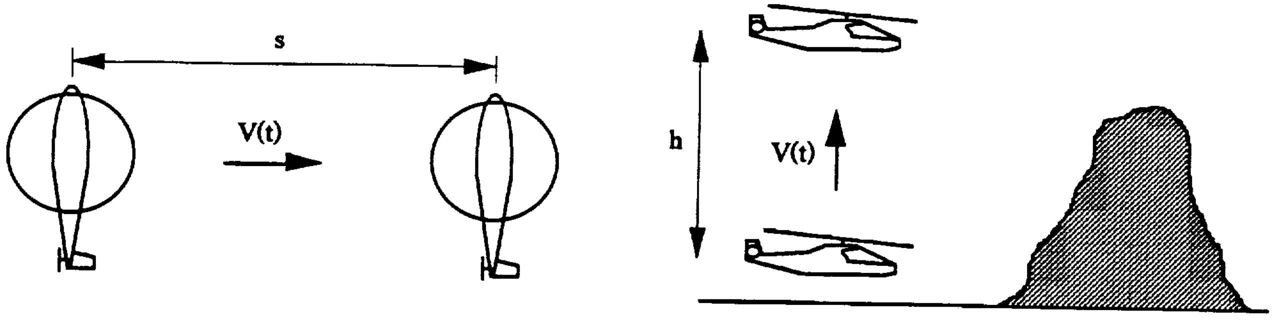


Figure 1 Velocity Profile for Acceleration and Deceleration Manoeuvre Using a 6th Order Polynomial

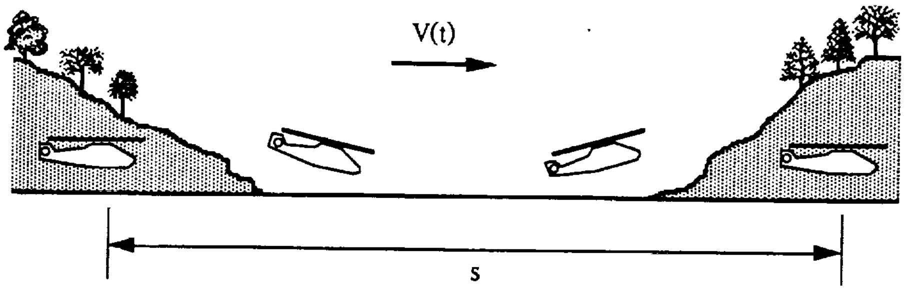
This velocity profile, shown in Figure 1, can be applied to any of the three component axes of the helicopter to give quick-hop (x), sidestep (y) and bob-up (z) manoeuvres, Figure 2.



a) The Sidestep

b) The Bob-up

Figure 2 Acceleration and Deceleration Manoeuvres



c) The Quick-hop

Figure 2 Continued

To establish the validity of the mathematical representation of a manoeuvre it is necessary to have a sufficient quantity of appropriate data from flight testing to allow comparison to be made. In the context of inverse simulation this data should consist of vehicle component velocities and accelerations as well as its position throughout the manoeuvre. When a comprehensive set of vehicle data, including ground based tracking measurements, was made available, it was clear that these simple functions compared well with the measured data [11]. However, subsequent analysis, reported below in section 3.3, has revealed that a direct comparison of velocities does not provide the appropriate measure of discrimination between candidate profiles and that the profile of equation (3) is not sufficiently aggressive to represent a MTE. Because of the smoothness of the global approximation described earlier in this section it is termed a ' non-aggressive' profile.

2.3.2 Mathematical Representation of Manoeuvres Using Piecewise Polynomial Functions

For the current work a series of models of the Mission Task Elements detailed in the ADS-33C document have been used. When these models were first created, [10] there was little published data on which to base the functions representing the geometry, or indeed the velocity or acceleration profiles, of the MTEs. The ADS-33C document itself gives clear descriptions of the MTEs in terms of performance levels which must be reached in key phases of the MTEs, but stops short of presenting an additional definitive geometry or positional time history. This is of course necessary, as imposing a rigid flight profile on top of a series of performance related targets will lead to a task with intolerable pilot workload. Thus, although the MTEs are described in sufficient detail for piloting purposes, further information is needed to describe the MTE in mathematical terms.

Care was taken when creating the mathematical models of the MTEs to encompass all of the features described in the ADS-33C document. For example, the key elements of the Rapid Sidestep MTE are described as follows

"Starting from a stabilised hover, ... initiate a rapid and aggressive lateral translation at approximately constant heading up to a speed of between 30 and 45 knots. Maintain 30 to 45 knots for approximately 5 seconds followed by an aggressive lateral deceleration back to the hover."

The following performance is also required

maintain the cockpit station within ±3m of the ground reference line,

altitude is to be maintained within ±3m,

maintain heading within ±10 degrees,

attain maximum achievable lateral acceleration within 1.5 seconds of initiating the manoeuvre,

attain maximum achievable deceleration within 3 seconds of initiating the deceleration phase.

It is quite clear from this description that the non-aggressive profile given by equation (3) will not meet all of these requirements. Instead, an alternative approach has been adopted where the MTE is considered as a sequence of polynomial sections where each section is chosen to represent one or more primary manoeuvre parameters of the MTE. A piecewise smooth function, involving one or more of the manoeuvre parameters for the whole MTE, can then be constructed. For the Rapid Sidestep described above there are five distinct sections, and after consideration of the ADS-33C description, it was decided that the most appropriate variable to specify was the vehicle's flight acceleration. This acceleration profile is shown in Figure 3, and the five sections consist of :

i) a rapid increase of lateral acceleration to a maximum value of $\dot{V}_{max}$ after a time of t_a seconds,
ii) a constant acceleration section to allow the flight velocity to approach its required maximum value, V_{max},
iii) a rapid transition from maximum acceleration to maximum deceleration $\dot{V}_{min}$ in a time of t_d seconds,
iv) a constant deceleration to allow the flight velocity to be reduced towards zero,
v) a rapid decrease in deceleration bringing the helicopter back to the hover.

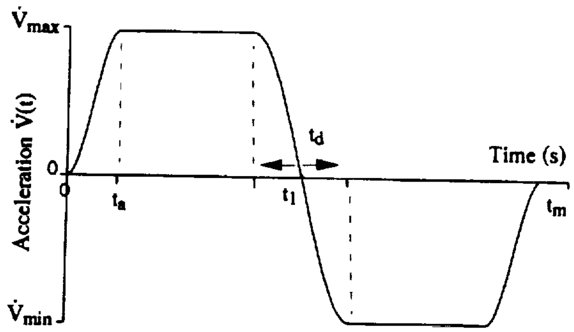


Figure 3 Piecewise Polynomial Representation of an Acceleration Profile for a Rapid Sidestep MTE

The control strategy and state time histories which this profile produces will be discussed in section 3.3. The values of $\dot{V}_{max}$ and $\dot{V}_{min}$ are inputs (effectively dependent on the vehicle being simulated) whilst in order to ensure that the performance limits are met, the values of t_a and t_d are set such that

$$t_a < 1.5\text{s} \quad \text{and} \quad t_d < 3.0\text{ s}$$

Referring to Figure 3, the times t_l and t_m are calculated to give

$$\int_0^{t_l} \dot{V}(t)\,dt = V_{max} \qquad \text{and} \qquad \int_{t_l}^{t_m} \dot{V}(t)\,dt = 0$$

where V_{max} is the maximum velocity reached during the manoeuvre and from Reference 1 is required to be such that $30 < V_{max} < 45$ knots. The transient acceleration profiles are expressed a cubic functions of time so that, for example in the range $t < t_a$,

$$\dot{V}(t) = [-2\left(\frac{t}{t_m}\right)^3 + 3\left(\frac{t}{t_m}\right)^2]\,\dot{V}_{max} \qquad (4)$$

The other performance requirements are readily incorporated into an inverse simulation. For example, heading can be constrained to be constant, whilst constant altitude flight along a reference line is guaranteed by ensuring that the off-axis components of velocity are set to zero. The only feature of the Rapid Sidestep MTE as given in ADS-33C which has been disregarded is the necessity to maintain the maximum velocity, lateral flight state between the acceleration and deceleration phases of the manoeuvre for approximately 5 seconds. For the purposes of flight trials this 5 second period may yield useful information on the handling characteristics of the vehicle - for example, poor handling might be indicated if any transient motions present in the vehicle's response do not diminish rapidly once the steady flight state had been attained. For inverse simulation this 5 second period would be modelled as a constant velocity, straight line flight path, and the calculated vehicle response would consist simply of a series of identical trim states. This will yield little useful information, and this phase of the MTE has therefore been ignored.

Developed in this way, in order to capture the aggressive nature of the MTE, the piecewise representation is termed an 'aggressive profile'. A comparison of sidestep manoeuvres generated by both aggressive and non-aggressive profiles can be obtained by differentiating equation (4) to obtain the acceleration for the global polynomial definition. This comparison is shown in Figure 4 from which it is apparent that if the manoeuvre is to be performed in the same time for both cases, then the peak acceleration encountered will be significantly greater in the global polynomial case. This effect is discussed further in section 3.3.1.

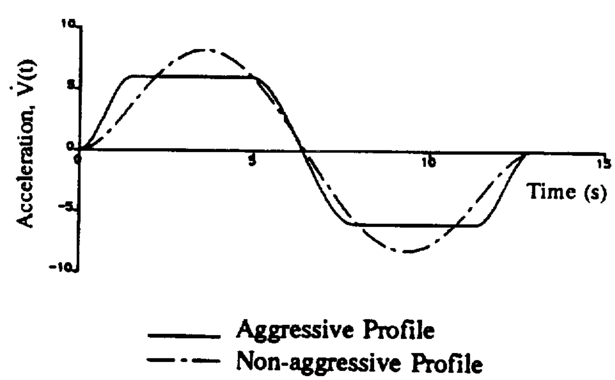


Figure 4 Comparison of Acceleration Profiles for Rapid Sidestep MTE

Not all of the MTEs described in Reference 1 can be converted in quite such a straightforward manner as the Rapid Sidestep described above. For example, the Pull-up/push-over which is described only in terms of the load factor profile requires the imposition of additional criteria to complete the flight-path definition. In creating the mathematical representations of the MTEs used here, certain assumptions have been made based mainly on the experience gained modelling the earlier NOE manoeuvres. As further information on flight testing using MTEs becomes available it will be possible to validate these models, and improve them as necessary.

3. Inverse Simulation as a Tool for Handling Qualities Assessment

In this section several approaches to handling qualities assessment through inverse simulation are discussed, and some examples are presented to illustrate their effectiveness. Comparisons are made between the results obtained for two configurations of the same helicopter, a battlefield/utility type (based on the Westland Lynx). The baseline configuration, Helicopter 1, has a mass of 3500 kg, and a rotor which is rigid in flap. The second configuration, Helicopter 2, differs from Helicopter 1 in that it has a fully articulated rotor and is 500 kg heavier, the increase in mass causing the centre of gravity to shift approximately 7.5cm aft of a position directly below the rotor hub. The aim here was to create two configurations with a high degree of similarity (both have identical fuselage and rotor aerodynamic characteristics, for example), but with differing performance and agility characteristics.

3.1 Confirmation of Helicopter Performance when Flying Mission Task Elements

Although ADS-33C [1], is directed towards handling qualities, it is unavoidable that the Mission Task Elements that form part of the aggressive task requirements contain a significant element of performance related criteria which refer to the particular configuration being flown. Therefore, the ability to confirm that an existing or projected design can satisfy the criteria, in a performance sense, over the full range of MTEs is of some significance. Section 2.3 discussed how the descriptions of MTEs given in Reference 1 may be converted to a flight path trajectory definition. When the definition is complete, the availability of an inverse simulation enables a range of performance criteria of candidate helicopters to be investigated against configuration parameters - such as control limits, rotor stiffness and installed power. While it is recognised that these criteria may not be the primary considerations which drive the design of the helicopter, inverse simulation can quickly establish the performance limitations of a given design over the full range of MTEs. The following example has been chosen to illustrate this facility.

3.1.1 Comparison of Performance in the Transient Turn MTE

This particular MTE is of interest as, in order to fly it, high roll rates and large roll angles are inevitable, and the parametric differences between the two configurations will have a marked effect on the control time histories generated by inverse simulation.

a) Mathematical Description of the Transient Turn MTE

The main features of this MTE, as described in Reference 1, are that a 180 degree heading change should be completed within 10 seconds of initiating the manoeuvre at a flight velocity of 120 knots. Previous experience of creating models of turning manoeuvres [10] has indicated that the most appropriate parameter to specify is the vehicle turn rate. Following the technique used to model the Rapid Sidestep MTE discussed in section 2.3, the transient turn is assumed to be composed of three distinct sections, as shown in Figure 5 and described below :

i) from a rectilinear flight trajectory, the turn rate is increased rapidly to some maximum value, $\dot{\chi}_{max}$,
ii) the turn rate is maintained at the maximum value until the heading approaches 180 degrees,
iii) the turn rate is rapidly decreased to zero thereby returning the vehicle to straight line flight.

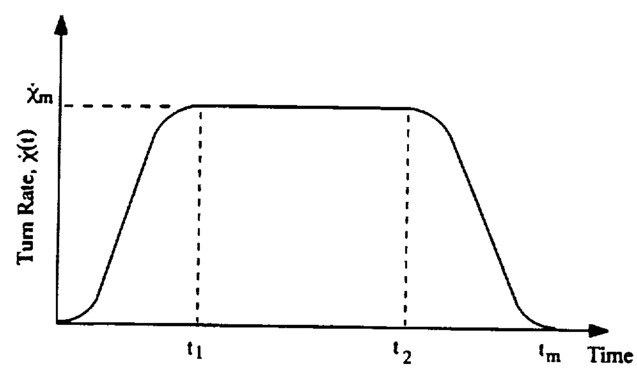


Figure 5 Turn Rate Profile for a Transient Turn MTE

This turn rate profile will force the simulated helicopter to roll to an appropriate bank angle, then hold this angle until the 180 degree heading change is approached, at which point the aircraft will be rolled in the opposite direction to return to straight line flight. If it is further assumed that constant altitude is desirable, and that to perform the task as quickly as possible, the entry speed of 120 knots is maintained

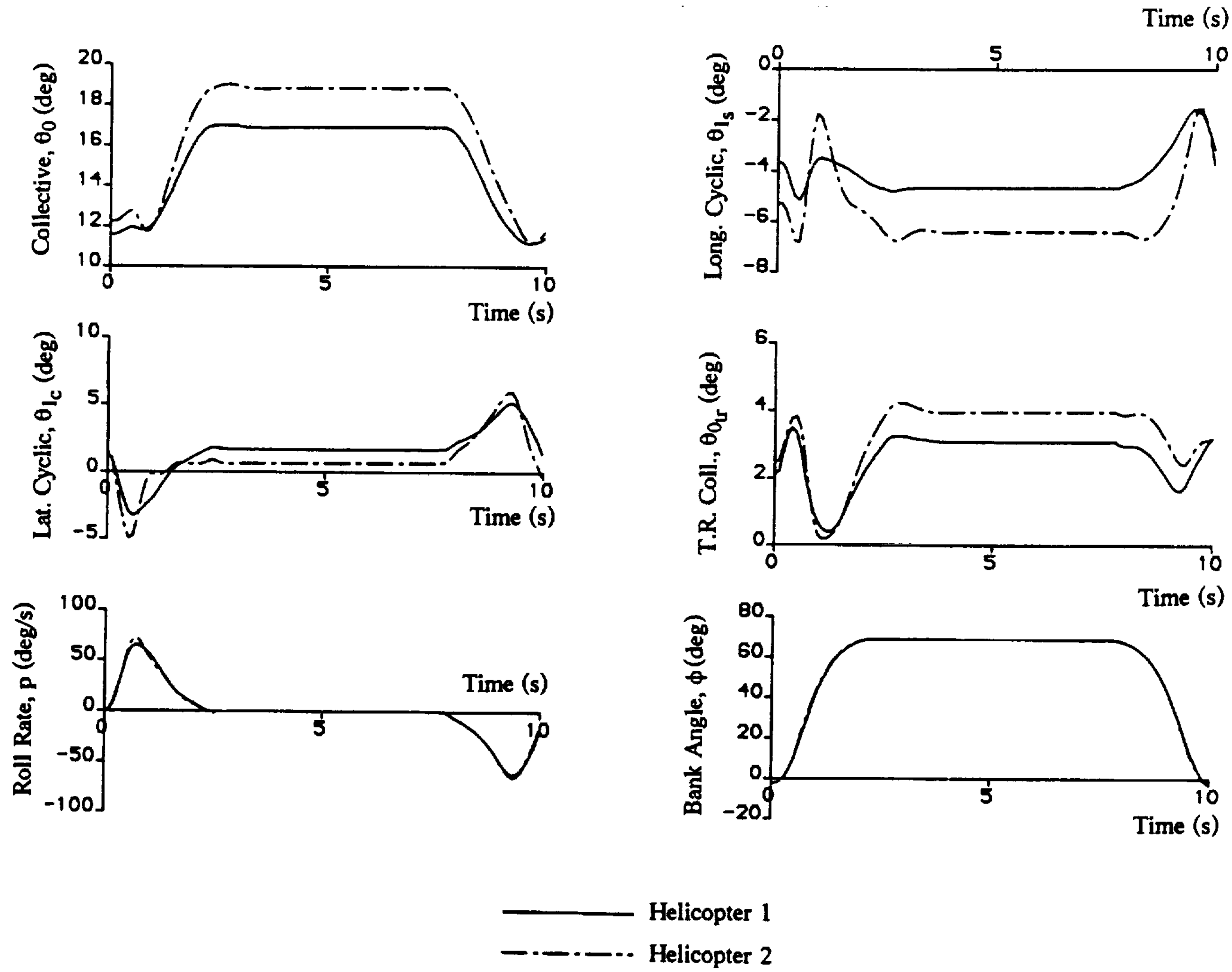


Figure 6 State and Control Time Histories from Inverse Simulation of a Transient Turn MTE

throughout, then the turn rate profile shown in Figure 5 is sufficient to obtain the required mathematical representation. A full description of how the flight path can be obtained from the turn rate profile and airspeed is given by Thomson and Bradley, [10], but the basic principle involves varying the maximum turn rate, $\dot{\chi}_{max}$, until the manoeuvre is completed within 10 seconds, and the heading change (effectively the area under the turn rate profile in Figure 5) is 180 degrees. This situation is reached when the turn radius is 155m and the resulting maximum normal load factor is 2.75. Note that the fraction of the manoeuvre spent in the entry and exit transients must also be specified and in this case a value of 15% was chosen after examination of flight test data from similar manoeuvres [8].

b) Inverse Simulation of Two Configurations Flying Transient Turn MTE - Control Strategy

Having defined the helicopter configurations and specified the manoeuvre, it is possible to perform inverse simulations of the two configurations flying it. The control time histories generated are shown in Figure 6, from which the overall control strategy can be deduced. The manoeuvre is initiated by a pulse in lateral cyclic to roll the aircraft, note that there is little difference in the amount required between the two configurations. As the aircraft rolls, also shown in Figure 6, collective (and hence thrust) must be added to maintain altitude. There is also a forward motion of the longitudinal stick (denoted by negative longitudinal cyclic) to maintain constant forward speed. The manoeuvre is performed without sideslip and tail rotor collective is used to ensure this condition is met. The initial pulse in lateral cyclic is opposed by a similar pulse in tailrotor collective which then increases beyond its level flight trim position to offset the extra torque produced by increased main rotor collective. The main differences between the time histories of the two aircraft lie in the collective and longitudinal plots. The baseline configuration, Helicopter 1, requires less collective firstly because it is lighter, but one must also consider the effect of shifting the centre of gravity aft of the rotor hub. This produces a nose up pitching moment which must be countered by forward stick if velocity is to be maintained, which explains the 2 degrees of extra forward longitudinal cyclic required by the less agile configuration, Helicopter 2. The longitudinal tilt of the thrust vector is in addition to the lateral tilt required for rolling, and hence is a contributory factory in the 2.5 degrees of extra collective required by Helicopter 2. Examination of Figure 6 shows that the roll angle history which was suggested by the manoeuvre definition is obtained, and the maximum bank angle reached was approximately 70 degrees, with roll rates of approximately 70 degrees/second encountered in the transients.

c) Inverse Simulation of Two Configurations Flying Transient Turn MTE - Confirmation of Performance

The advantage of using inverse simulation becomes apparent when it is realised that the collective limit of this configuration is 20 degrees. Consequently, on examination of the collective time history in Figure 6, it is clear that Helicopter 2 is close to the limiting case for this manoeuvre. It then follows that the limiting case for various aircraft masses and centre of gravity positions could be obtained by repeated inverse simulation of the manoeuvre thereby allowing the aircraft configuration envelope for this MTE to be derived. This type of investigation may be extended to include a range of MTEs and configurational parameters.

For performance comparisons the application of inverse simulation is clear cut. Given the availability of a helicopter model of appropriate validity, it is straightforward to measure comparative control margins and control activity for a given set of manoeuvres. Experience has shown that the facilities offered by flight mechanics models such as HGS are adequate for such investigations. Therefore the remaining task is to compile a suite of validated manoeuvre definitions - and although several of the descriptions of Reference 10 have been validated against flight data there are several manoeuvres for which flight tests are required to provide practical validation. The conclusion to be drawn is that while performance comparisons of this kind are straightforward to conduct, the handling qualities information that it can provide is limited and likely to remain so.

3.2 The Handling Qualities Index

One of the earliest applications of inverse simulation was an attempt to quantify the agility of a given helicopter configuration through an Agility Performance Index (API) [12]. The difficulty of producing a general definition of the term agility is well known [4] but the API was based on the concept of installed agility, that is, it was dependant on the particular configuration of the helicopter and independent of any pilot model. This independence of a pilot model is a feature of the inverse formulation since it generates a precise piloting task and leaves no scope for other than ideal piloting of the helicopter. The API of a helicopter for a given manoeuvre was determined from the formula:

$$\mathrm{API} = \sum_{i=1}^{n_s} q_i \int_0^{t_m} f\big(x_i(t)\big)\, dt \; + \; \sum_{j=1}^{n_c} r_j \int_0^{t_m} g\big(u_j(t)\big)\, dt \qquad (5)$$

where t_m is the time taken to complete the manoeuvre, q_i and r_j are weighting constants related to state i and control j. The integers n_s and n_c are the number of states and controls to be included in the performance index. The functions $f(x_i(t))$ and $g(u_j(t))$ were selected to penalise large state and control deviations during the manoeuvre: for example,

$$f(x_i(t)) = \left[\frac{x_i(t) - x_{i_{trim}}}{x_{i_{max}} - x_{i_{trim}}}\right]^2$$

where $x_{i_{trim}}$ is the value of state i, in the steady flight condition at the entry to the manoeuvre, and $x_{i_{max}}$ is the maximum value of the state encountered during the manoeuvre. Using this definition low values of API (i.e. small control and state displacements) will imply good agility. The obvious difficulty with such an approach is the appropriate choice of the weights q_i and r_j and, in practice, zero or unity were commonly employed in comparative studies of different helicopter configurations on the basis of whether it was felt that those quantities were significant or not in a particular manoeuvre. Nevertheless, despite this simplified approach, the work established the principle whereby different helicopters could be comparatively assessed for their agility over a range of standard manoeuvres by a reproducible simulation study.

Having established the principle for agility studies, it is attractive to consider a similar approach for handling qualities and define a Handling Qualities

Index (HQI) using a similar form to that in equation (5). It may be necessary to include other terms such as auto- and cross-correlations of the control responses but from the whole of the attitude, rate, velocity, acceleration and control information, it should not be unreasonable to expect that an appropriate balance of the coefficients in the formulation of the HQI could produce a formula which reflects, in large measure, an assessment of handling qualities. Unfortunately, the question of finding the values of the coefficients necessary to achieve the appropriate balance is impracticable - just as in the case of the API. Therefore, although conceptually attractive and demonstrable in principle, the HQI falls at the present time because of the lack of essential knowledge about the coefficient values, and if it were to be seriously considered for development in the future then an extensive validation programme would be needed to establish its credibility.

3.3 Quickness Parameters

In addition to the calculation of the time responses of the control displacements, inverse simulation of a given manoeuvre calculates the responses of the full range of kinematic variables. Included in this information, are the time-histories of roll rate p and roll angle ϕ, so that when a Rapid Sidestep manoeuvre is simulated according to the translation velocity profile defined by Figure 3 it is a straight forward matter to calculate the quickness parameter chart $p_{pk}/\Delta\phi_{pk}$ against $\Delta\phi_{min}$ in a manner described by the ADS-33C document, section 3.3. The time histories of p and ϕ shown in Figure 7 for the sidestep manoeuvre with $t_a = 1.5$s, $t_d = 3$s, $V_{max} =$ 35 Knots, $\dot{V}_{max} = 5 m/s^2$ and $\dot{V}_{min} = -5\ m/s^2$, are obtained from the inverse simulation of Helicopter 1 for the Rapid Sidestep using the aggressive profile defined by Figure 3. They are annotated to show the calculations of the quickness parameters of the main pulses of roll rate. First there is the roll into the manoeuvre then, at about the midpoint, there is a roll in the opposite direction to bring the rotor into a position to decelerate the helicopter, and finally there is a roll back to the level, trim, position. The attitude quickness parameters corresponding to this data and data from a variety of similar manoeuvres (obtained by varying the parameters used to define the MTE model) are shown in Figure 8 and it can be seen that the values mainly lie in the Level 1 region.

The corresponding control displacement time-histories are shown in Figure 9 but it should be borne in mind that the attitude quickness parameters have been calculated solely as a result of a defined manoeuvre so are not, in the context of inverse simulation, necessarily an appropriate measure of the

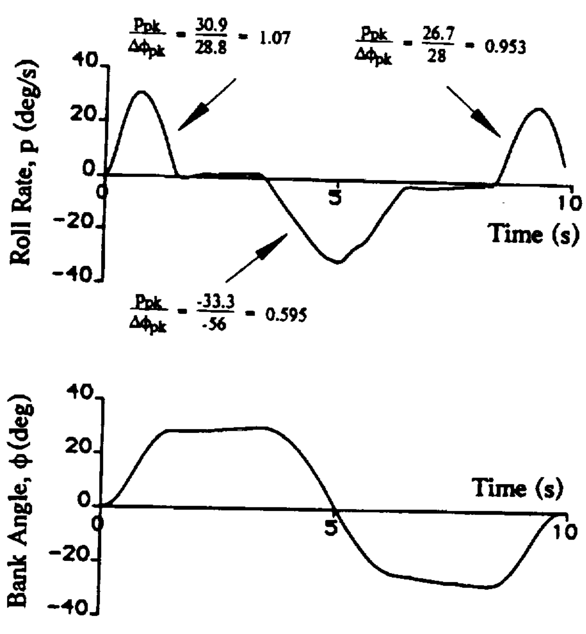


Figure 7 Calculation of Roll Quickness from Inverse Simulation of Helicopter 1 Flying a Rapid Sidestep MTE

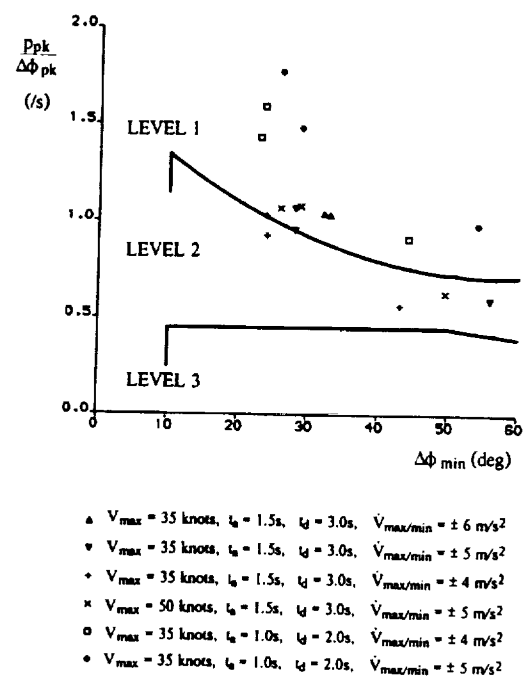


Figure 8 Roll Quickness Chart for Helicopter 1 from Inverse Simulation of Rapid Sidesteps

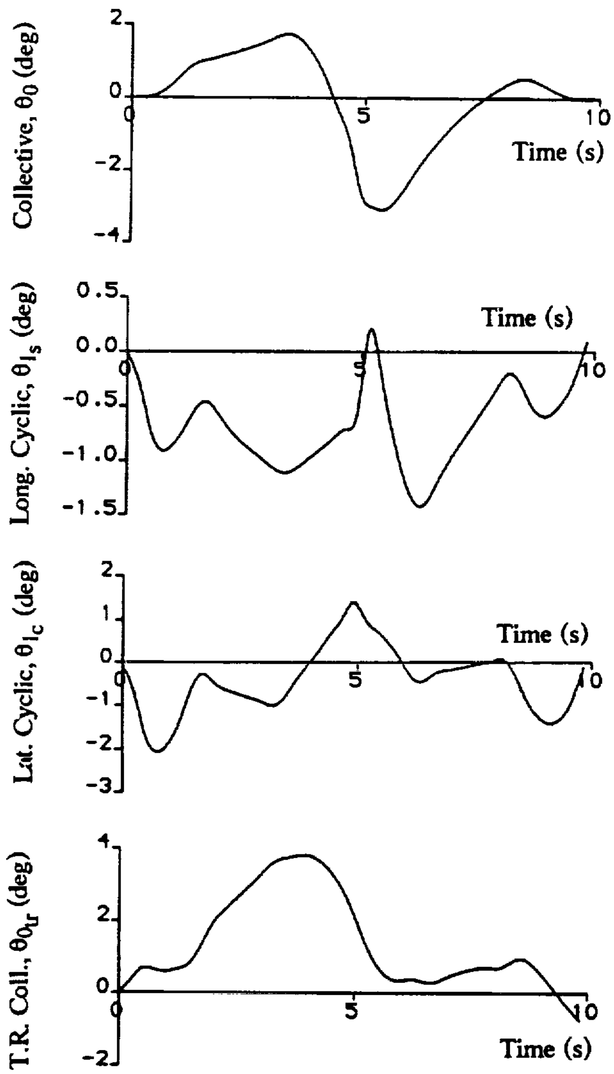


Figure 9 Control Displacements for Helicopter 1 Flying a Rapid Sidestep MTE

handling qualities of a particular configuration. These issues are further elaborated in sections 3.3.1 and 3.3.2 but before leaving the current discussion it is opportune to give some initial attention to the output of the inverse analysis - that is the set of control time histories - and pose the question of how to process it to afford some measure of handling quality or pilot workload. The lateral cyclic control displacement, θ_{1_c}, certainly does not have the characteristics of the bank angle so that the parameter $\dot{\theta}_{1_{cpk}}/\Delta\theta_{1_{cpk}}$ is unlikely to be useful - and indeed experimentation has shown this to be the case. In fact, it may be observed that the pulses of lateral cyclic away from the trim position are of a similar character to the pulses of roll rate, p, and this similarity suggests that Θ_{1_c}, the integral of θ_{1_c} :

$$\Theta_{1_c} = \int^{t} \theta_{1_c}(t)\ dt$$

relates to the value of the bank angle so that a control quickness parameter $\theta_{1_{cpk}}/\Delta\,\Theta_{1_{cpk}}$ may be the equivalent parameter, and when plotted against $\Delta\Theta_{1_c}$, would give a chart equivalent to that used to plot attitude quickness. The manner of calculation is identical to that of the attitude quickness as illustrated in Figure 10. That this quantity is a useful measure to invoke from the inverse simulation method is discussed in more depth in section to follow.

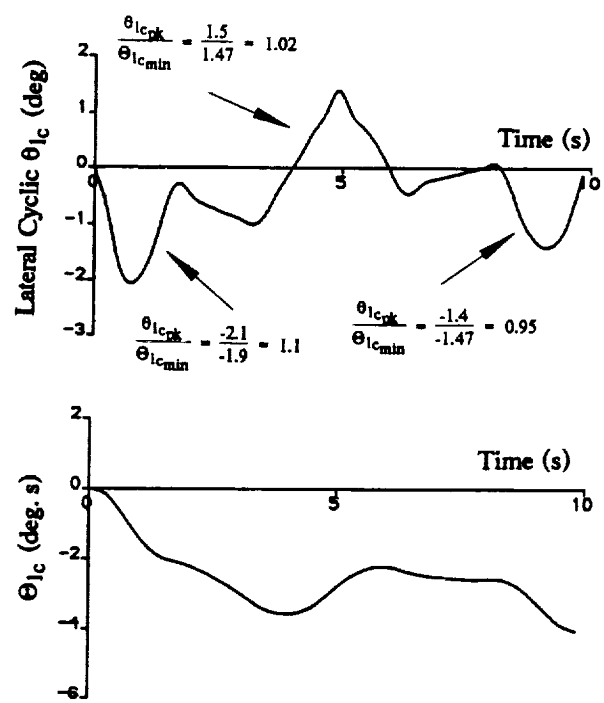


Figure 10 Calculation of Lateral Cyclic Quickness Parameter from Inverse Simulation of Helicopter 1 Flying Rapid Sidestep MTE

3.3.1 Influence of MTE Model

In this section we return to the issues raised above regarding the calculation of quickness parameters for predefined manoeuvres. The first aim of this discussion is to qualify the observations made on previous occasions that the details of the manoeuvre profile definition have not appeared to be significant. When faced with the requirement to specify the velocity profile of a sidestep MTE, for example, it is natural, as described in section 2.3.1 above, to write down in the first instance the non-aggressive profile, since it is the computationally simplest description. It gives a smoother change in acceleration than the aggressive profile described in section 2.3.2 as has been illustrated in Figure 4. When this manoeuvre is simulated using the Helicopter1 configuration, the attitude quickness parameters vary significantly from those derived from the more sharply executed aggressive manoeuvre and lie mainly in the Level 2 region as is shown in Figure 11. Here then is a further criterion by which to select a manoeuvre description:- if it is to be used for handling qualities studies within the ambit of ADS-33C then a description must be employed which sets the manoeuvre in the Level 1 region. The attitude quickness parameters have discriminated quantitatively between the aggressive and non-aggressive profiles, confirming the quantitative discrimination noted earlier.

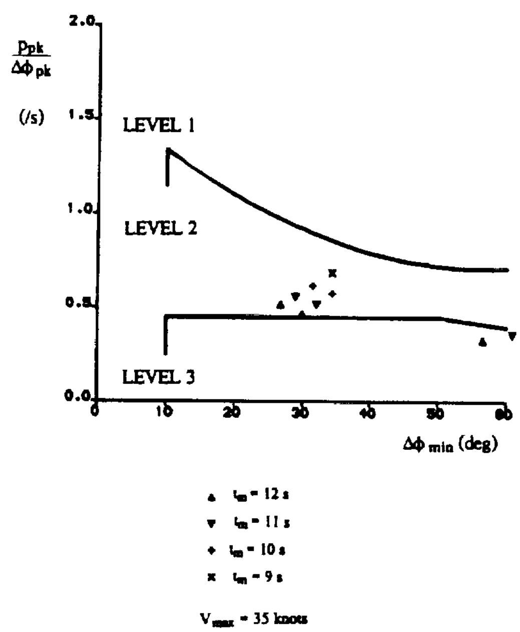


Figure 11 Roll Quickness Chart for Helicopter 1 from Inverse Simulation Using Non-aggressive Sidestep Profile

3.3.2 Influence of Configuration

Now consider the effect of altering the helicopter's configuration to a less agile version. The Helicopter 2 configuration of the vehicle has more weight and significantly reduced rotor stiffness. Applying the same manoeuvre to it produces, as seen in Figure 12, almost identical attitude quickness values - in fact occurring in closely positioned pairs. This result is typical of many simulations which have been conducted and which lead to the initially surprising conclusion that the attitude quickness parameters are largely independent of the configuration used in the inverse simulation. A little reflection will show that this effect is not unusual since the roll rates and attitude angles through a manoeuvre are largely dictated by the manoeuvre profile itself and one should expect some agreement for other than gross configurational changes.

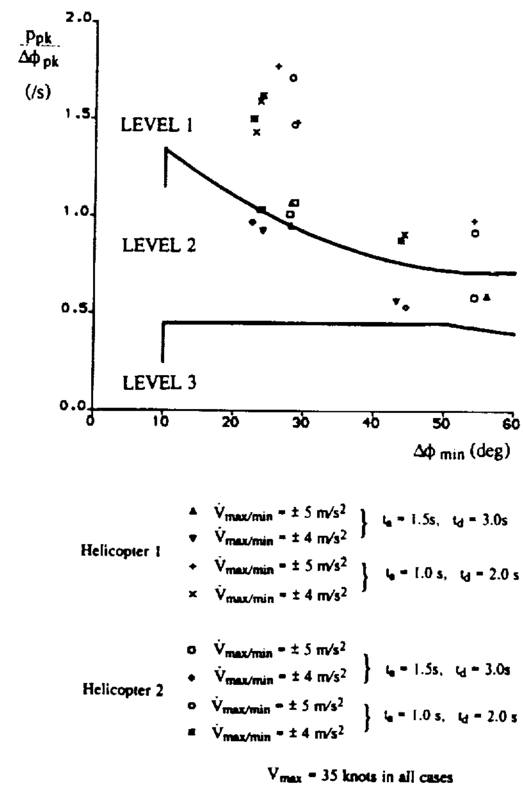


Figure 12 Roll Quickness Chart for 2 Configurations from Inverse Simulation of Rapid Sidestep MTE

However, the control quickness *is* influenced by the variation in configuration. Figure 13 shows quite clearly that it increases significantly for the Helicopter 2 configuration, representing the additional effort required by the pilot to drive the inferior configuration through the same manoeuvre. The control quickness parameter, as defined in Section 3.3, is remarkably effective in discriminating between different configurations.

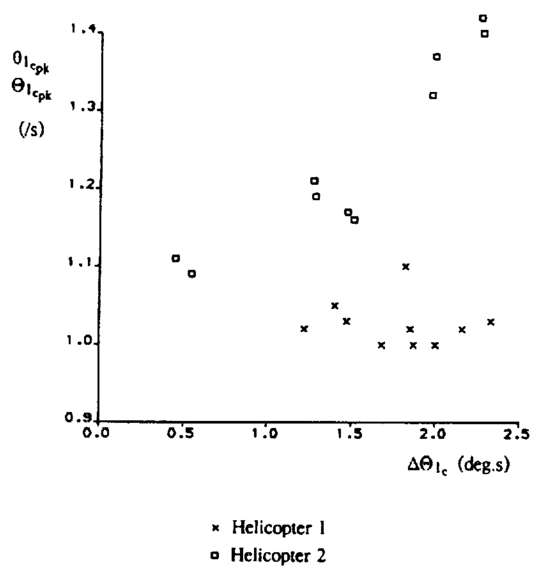


Figure 13 Lateral Cyclic Quickness Chart for 2 Configurations from Inverse Simulation of Rapid Sidestep MTE

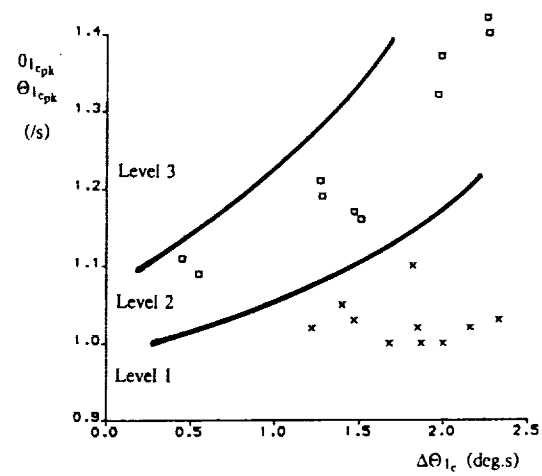


Figure 14 Lateral Cyclic Quickness Chart with Suggested Workload/Handling Qualities Boundaries

3.4 Handling Criteria

These simple illustrations suggest a procedure to be followed when using inverse simulation for handling qualities studies. One must use the requirements, such as ADS-33C, in an inverse manner. First the manoeuvre must be refined until it satisfies the level of handling demanded by the requirements regarding attitude quickness, then various configurational changes can be compared by examining the corresponding control quickness values. An increase in the value of the control quickness indicates an increased work load and hence a worsening of the handling qualities. In addition to there being a relative measure it may be possible, as indicated speculatively on Figure 14 to identify regions in the control quickness chart which correspond to particular levels of pilot workload or handling rating.

4. Conclusions

The potential of three approaches for employing inverse simulation to assess handling qualities have been discussed. Two of them, the Handling Qualities Index and the performance comparisons have been shown to have limited potential while the third, the use of attitude and control quickness parameters in a dual relationship, promises useful exploitation.

Two general conclusions may be made about the current state of inverse simulation:

(a) Current mathematical models, such as HGS, are adequate for basing inverse flight mechanics studies on.

(b) Flight tests should be made to validate the flight-path models currently being developed.

The main conclusion of this work resides in the significance of the quickness parameters in association with inverse simulation.

It is important to emphasise that these investigations have indicated a practical criterion for deciding on the appropriate modelling of an MTE for inverse simulation. That is, the model must generate attitude quickness parameters which lie in the Level 1 region. Moreover, the choice of manoeuvre model is practically independent of helicopter configuration. Therefore, referring to the conditions set out in the introduction, this is the sense in which manoeuvres must be representative.

The approach has been taken further and it has been shown to be possible to define a control quickness parameter which can discriminate between different helicopter configurations flying the same manoeuvre. While it is acknowledged that the choice of definition for the control quickness may require future development, it is clear from the work done so far that this general approach can potentially extend the scope of simulation in demonstrating compliance with handling qualities requirements. It does appear from this work that in using quickness parameters the conditions are sufficient for the successful use of inverse simulation providing that it is realised that it is the control quickness that is the determining factor in the assessment.

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References

1. Anon, "Aeronautical Design Standard, Handling Qualities Requirements for Military Rotorcraft." ADS-33C, August 1989.

2. Bradley, R., Padfield, G.D., Murray-Smith, D.J., Thomson, D.G., "Validation of Helicopter Mathematical Models." Transactions of the Institute of Measurement and Control, Vol. 12, No. 4, 1990.

3. Thomson, D.G., Bradley, R., "Development and Verification of an Algorithm for Helicopter Inverse Simulation." Vertica, Vol. 14, No. 2, May 1990.

4. Whalley, M.S., "Development and Evaluation of an Inverse Solution Technique for Studying Helicopter Maneuverability and Agility." NASA TM 102889, July 1991.

5. McKillip, R.M., Perri, T.A., "Helicopter Flight Control System Design and Evaluation for NOE Operations Using Controller Inversion Techniques." 45th Annual Forum of the American Helicopter Society, Boston, May 1989.

6. Padfield, G.D., "A Theoretical Model for Helicopter Flight Mechanics for Application to Piloted Simulation." Royal Aircraft Establishment, TR 81048, April 1981.

7. Thomson, D.G., "Development of a Generic Helicopter Mathematical Model for Application to Inverse Simulation." University of Glasgow, Department of Aerospace Engineering, Internal Report No. 9216, June 1992.

8. Thomson, D.G., Bradley, R., "Modelling and Classification of Helicopter Combat Manoeuvres." Proceedings of ICAS Congress, Stockholm, Sweden, September 1990.

9. Taylor, C.D., Thomson, D.G., Bradley, R., "The Mathematical Definition of Helicopter Take-off and Landing Manoeuvres for Offshore Operations." University of Glasgow, Department of Aerospace Engineering, Internal Report No. 9243, October 1992.

10. Thomson, D.G., Bradley, R., "The Use of Inverse Simulation for Conceptual Design." 16th European Rotorcraft Forum, Glasgow, September 1990.

11. Thomson, D.G., Bradley, R., "Validation of Helicopter Mathematical Models by Comparison of Data from Nap-of-the-Earth Flight Tests and Inverse Simulations." Paper No. 78, Proceedings of the 14th European Rotorcraft Forum, Milan, Italy, September 1988.

12. Thomson, D.G., "An Analytical Method of Quantifying Helicopter Agility." Paper 45, Proceedings of the 12th European Rotorcraft Forum, Garmisch-Partenkirchen, Federal Republic of Germany, September 1986.