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THE CONTRIBUTION OF INVERSE SIMULATION TO THE 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 helicopter 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 shown to be capable of discriminating between piloting tasks of flying two different configurations through the same manoeuvre.

Nomenclature

p, q, r	components of aircraft angular velocity in body axes
Q	quickness parameter
t_a	time to reach maximum acceleration in Rapid Sidestep MTE
t_d	time to reach maximum deceleration in Rapid Sidestep MTE
t_1	time in acceleration phase of Rapid Sidestep MTE
t_m	time taken to complete manoeuvre
$\mathbf{u}$	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
$\mathbf{x}$	state vector
$\mathbf{y}$	output vector
ϕ, θ, ψ	aircraft attitude angles
θ_0	main rotor collective pitch angle
Θ_{1_c}	time integral of lateral cyclic pitch
$\theta_{1_s}, \theta_{1_c}$	longitudinal and lateral cyclic pitch angles
$\theta_{0_{tr}}$	tail rotor 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 an 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. Previous work, [4] has shown how performance comparisons and handling qualities indices may be obtained from inverse simulation, but this paper concentrates on the calculation of quickness parameters. In the section that follows some of the main features of inverse simulation and manoeuvre description are discussed.

This application of inverse simulation 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 [5, 6] 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:

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

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

where **x** is the state vector of the system and **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 **u**. The output equation, (2), is a statement of how the observed output vector **y** is obtained from the state vector.

Inverse simulation is so called because, from a pre-determined output vector **y** it calculates the control time-histories required to produce **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 **u**, inverse simulation places emphasis on the careful definition of the required output **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 $\mathbf{u} = [\theta_0\ \theta_{1_s}\ \theta_{1_c}\ \theta_{0_{tr}}]^T$. The main rotor thrust is controlled by the collective pitch lever, θ_0, whilst the pitching and rolling moments are controlled by the longitudinal and lateral cyclic stick inputs θ_{1_s} and θ_{1_c} respectively. Yaw and sideslip control is achieved be use of pedal, or tail rotor collective inputs, $\theta_{0_{tr}}$. 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 **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 [7]; 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), [8] 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 [9], Air-to-air Combat, Off-shore Operations [10], and of particular interest in this study, Mission Task Elements [11]. There is also a facility for accessing flight test data.

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 of 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

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

where t_m is the time taken to complete the manoeuvre.

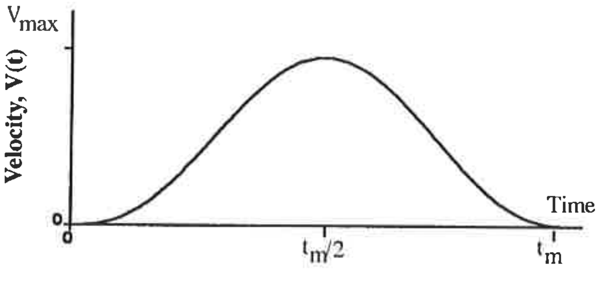
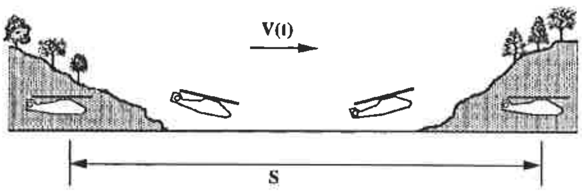
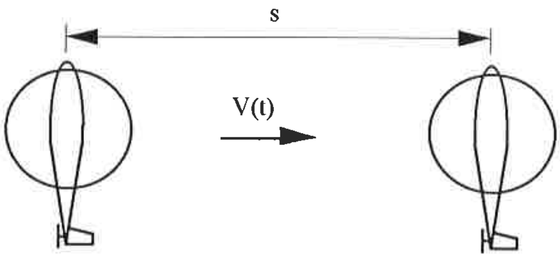


Figure 1 Velocity Profile for Acceleration and Deceleration Manoeuvre Using a 6th Order Polynomial

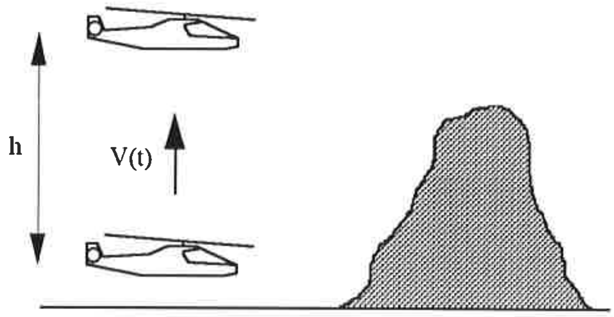
This velocity profile, shown in Figure 1, can be applied to any of the three component axes of the helicopter to give quick-hop (x), sidestep (y) and bob-up (z) manoeuvres, Figure 2.



(a) The Quick-hop Manoeuvre



(b) The Sidestep Manoeuvre



(c) The Bob-up Manoeuvre

Figure 2 Basic Helicopter Nap-of-the-Earth Manoeuvres

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 [12]. However, subsequent analysis, reported below in section 3.1, 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 an 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, [11] 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 at time t_m.

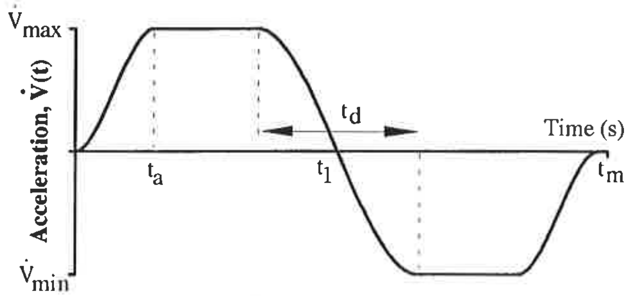


Figure 3 Piecewise Polynomial Representation of the Acceleration Profile for a Rapid Sidestep MTE.

The control strategy and state time histories which this profile produces will be discussed in section 3.1. 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

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

Referring to Figure 3, the times t_1 and t_m are calculated to ensure that

$$\int_0^{t_1} \dot{V}(t)dt = V_{max} \quad \text{and} \quad \int_{t_1}^{t_m} \dot{V}(t)dt = 0$$

where V_{max} is the maximum velocity reached during the manoeuvre and from Reference 1 is required to be such that $30 \leq V_{max} \leq 45$ knots. The remaining task is to define suitable functions for the transient acceleration profiles. For the range $t \leq t_a$, a cubic polynomial expression may be specified:

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

and similar cubic functions are found for phases (iii) and (v).

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. The inclusion of this relatively inactive phase of the MTE has been found to yield little useful information in the current work. It has therefore been ignored to help clarify the discussion in the following sections.

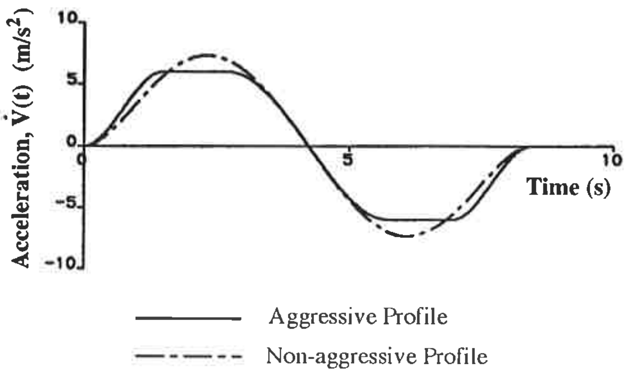


Figure 4 **Comparison of Aggressive and Non-aggressive Rapid Sidestep Acceleration Profiles**

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. Further, within the category of aggressive profiles, it is possible to control the aggressiveness by increasing the order of the polynomial defining the transient sections, for example, the cubic expression (4) may be replaced by the 5th order polynomial, (5).

$$\dot{V}(t) = \left[6\left(\frac{t}{t_a}\right)^5 - 15\left(\frac{t}{t_a}\right)^4 + 10\left(\frac{t}{t_a}\right)^3\right]\dot{V}_{max} \qquad (5)$$

The effect on the piecewise polynomial acceleration profile is shown in Figure 5. Although the initial increase of acceleration occurs more smoothly, the peak rate of change of acceleration will be greater as the maximum slope of the function is higher in the case of the 5th order polynomial.

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

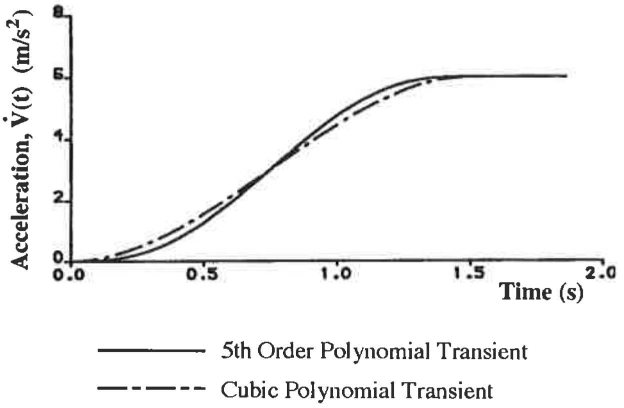


Figure 5 **Effect of Polynomial Order on Aggressiveness of the Initial Phase of the Piecewise Polynomial Acceleration Profile**

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.

3. Inverse Simulation as a Tool for Handling Qualities Assessment

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 of lower solidity and is 750 kg heavier, the increase in mass causing the centre of gravity to shift approximately 7.5cm further 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 Calculation of Quickness Parameters from Inverse Simulation Results

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 acceleration 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 6 for a sidestep manoeuvre with t_a = 1.5s, t_d = 3s, 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.

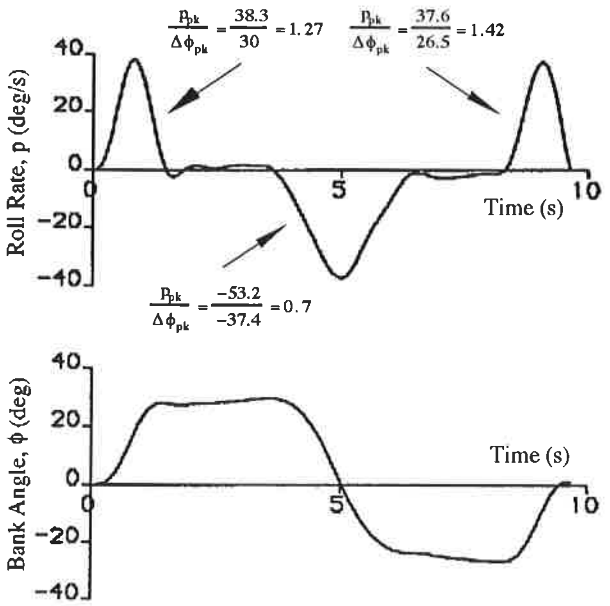


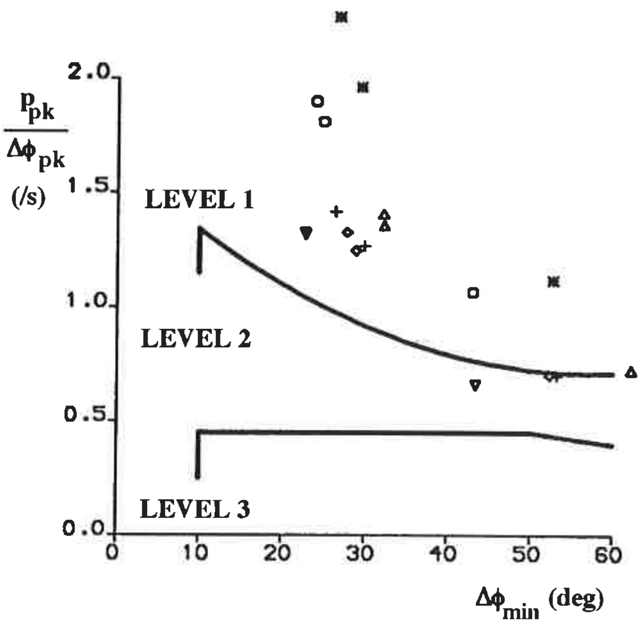
Figure 6 **Calculation of Roll Quickness from Inverse Simulation of Helicopter 1 Flying a Rapid Sidestep MTE**

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 7 and it can be seen that the values mainly lie in the Level 1 region.

3.2 The Control Quickness Parameter

The control displacement time-histories corresponding to Figure 6 are shown in Figure 8 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 handling qualities of a particular configuration. These issues are further elaborated in sections 3.4 and 3.5 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



▲ $V_{max} = 35$ knots, $t_a=1.5$s, $t_d = 3.0$s, $\dot{V}_{max/min} = \pm\, 6\text{m/s}^2$
\+ $V_{max} = 35$ knots, $t_a=1.5$s, $t_d = 3.0$s, $\dot{V}_{max/min} = \pm\, 5\text{m/s}^2$
▼ $V_{max} = 35$ knots, $t_a=1.5$s, $t_d = 3.0$s, $\dot{V}_{max/min} = \pm\, 4\text{m/s}^2$
◆ $V_{max} = 50$ knots, $t_a=1.5$s, $t_d = 3.0$s, $\dot{V}_{max/min} = \pm\, 6\text{m/s}^2$
○ $V_{max} = 35$ knots, $t_a=1.0$s, $t_d = 2.0$s, $\dot{V}_{max/min} = \pm\, 4\text{m/s}^2$
✱ $V_{max} = 35$ knots, $t_a=1.0$s, $t_d = 2.0$s, $\dot{V}_{max/min} = \pm\, 5\text{m/s}^2$

Figure 7 **Roll Quickness Chart for Helicopter 1 from Inverse Simulations of Rapid Sidesteps**

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 9. That this quantity is a useful measure to invoke from the inverse simulation method is discussed in more depth in section 3.5.

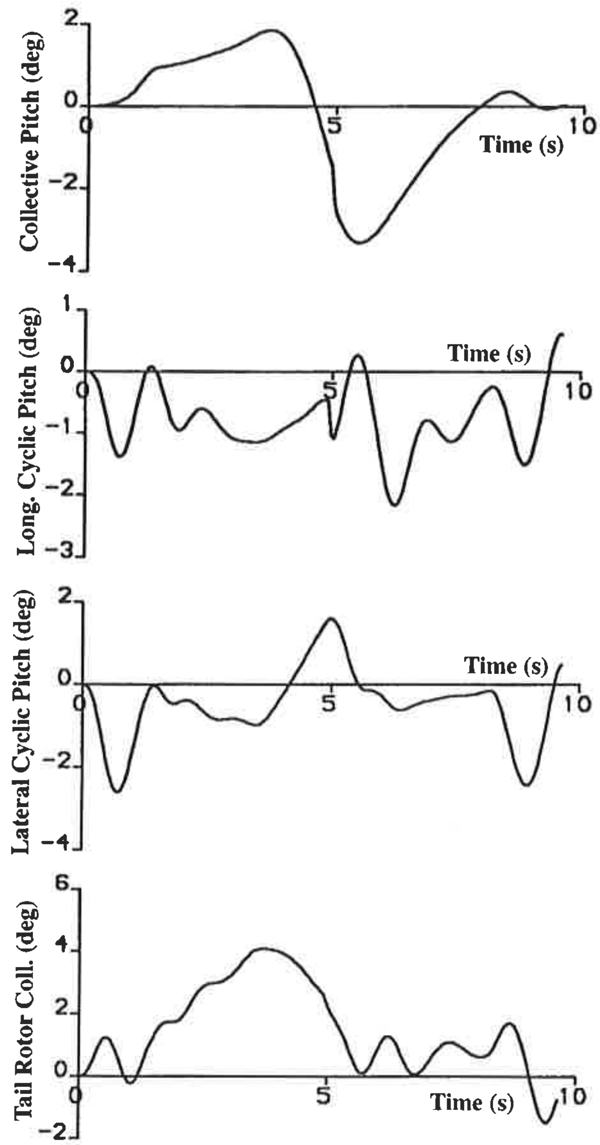


Figure 8 Control Displacements for Helicopter 1 Flying a Rapid Sidestep MTE

3.3 Automatic Calculation of Quickness Values

Where a response is made up of distinct pulses with well defined peaks it is a simple matter to supplement the manual calculation with software to produce quickness values automatically. A threshold is usually incorporated in the algorithm order to avoid the processing of small-amplitude peaks in the response that are not relevant to handling qualities. It has been found however, that some traces are such a complex combination of pulse features that there can be some ambiguity about the appropriate extraction of quickness data. For example, in Figure 9, the first pulse of lateral cyclic is in a negative direction but does not immediately return to cross the zero line. Therefore, the question arises as to whether or not the

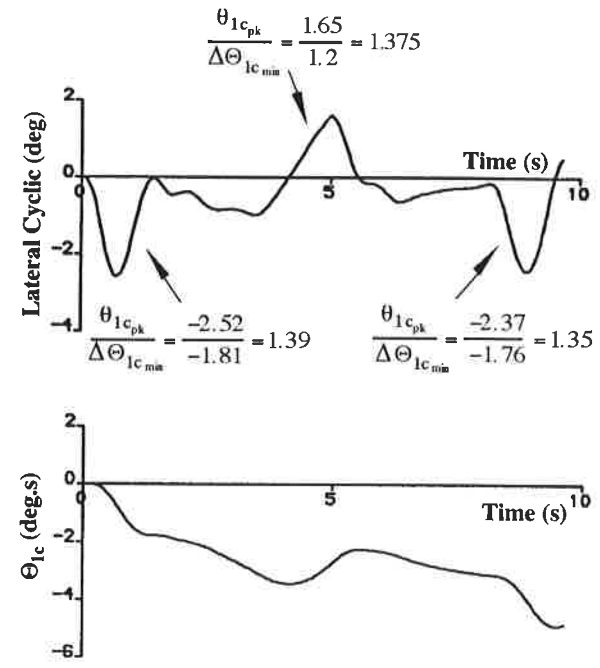
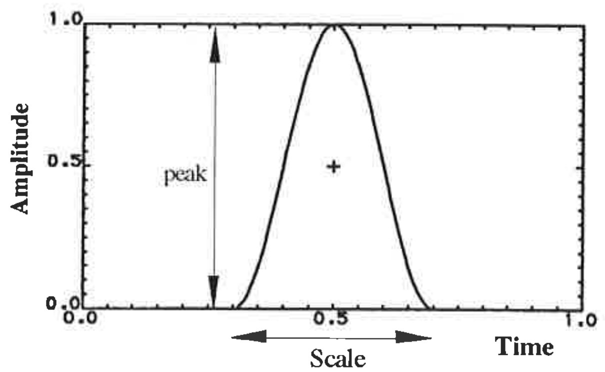


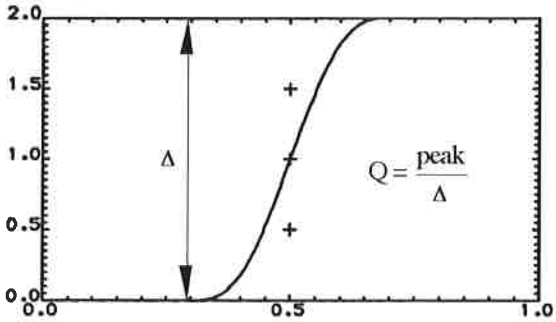
Figure 9 Calculation of Lateral Cyclic Quickness Parameter from Inverse Simulation of Helicopter 1 Flying Rapid Sidestep MTE

pulse is sufficiently well defined as to constitute an 'event' which can be properly allocated a quickness value. Infact, the situation is further complicated by a more indistinct pulse which follows the initial pulse and which may constitute either a second separate pulse or a continuation of the first. In this and similar cases, in order to obtain a consistent and repeatable processing of the responses, recourse has been taken, in the current research, to the relatively new area of wavelet analysis and the methods of Watson and Jones [13]. The aim of the analysis is to decompose a given response into its component positive wavelets (or pulses) of differing scales and amplitudes. The basic pulse, is shown in Figure 10.



(a) Peak Value

Figure 10 Elementary Pulse Wavelet and Integral



(b) Increment Δ and Quickness, Q

Figure 10 Continued

It has unit amplitude, arbitrary location and scale width. The first step is to correlate the given time history with elementary pulses of different scales and locations. The resulting matrix of information may be graphed as a correlation surface, Figure 11, and peaks and hollows in this surface indicate where there are, respectively, local maxima and minima in the correlation with respect to scale and location.

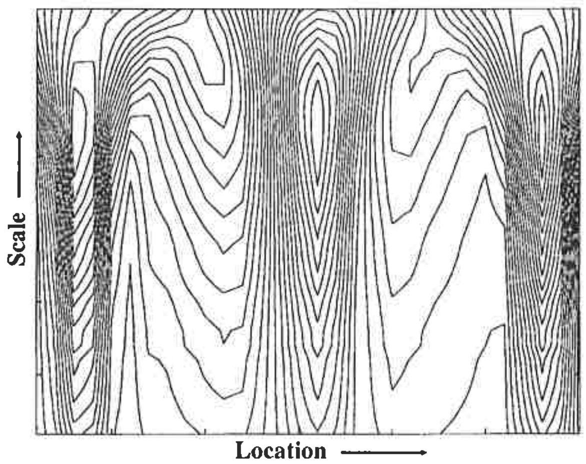


Figure 11 Correlation Surface for Lateral Cyclic of Figure 9

Therefore, one may deduce the existence of a component pulse, embedded in the given signal, whose magnitude is easily deduced from the value of the correlation extremum. The extrema in the correlation surface may be easily identified by scanning the correlation matrix. It is then a simple matter to calculate the quickness value for each component pulse and draw up the corresponding chart. It can be observed, in Figure 11, that there is a well defined extremum for the first but not for the poorly defined second pulse. As a consequence, the quickness value for the latter has not been shown on Figure 9.

3.4 Influence of MTE Model

In this section we return to the issues raised above regarding the calculation of attitude 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 profiles described in section 2.3.2 - as has been illustrated in Figure 4. When this manoeuvre is simulated using the Helicopter 1 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 12. 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 qualitative discrimination noted earlier.

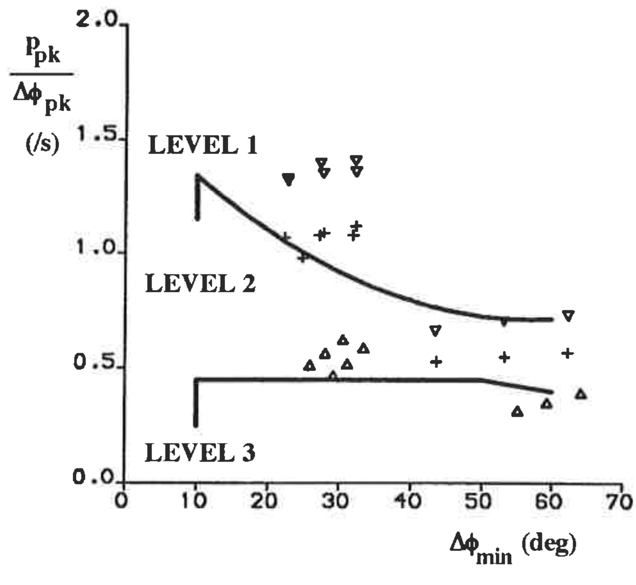
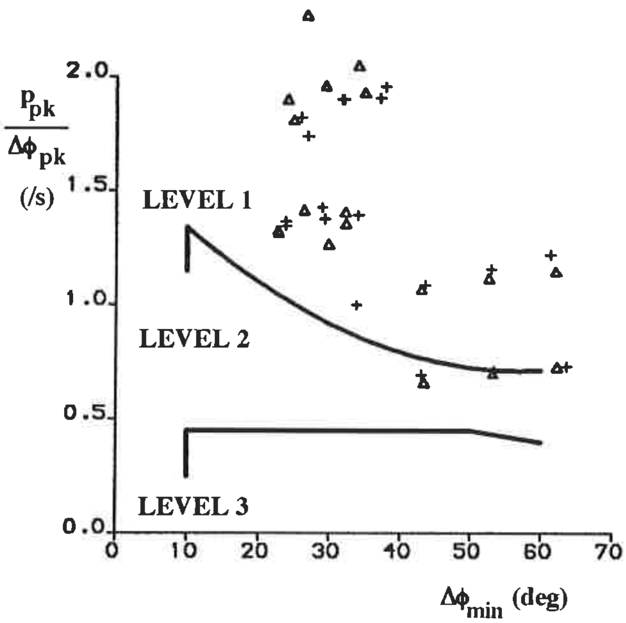


Figure 12 Roll Quickness Chart for Helicopter 1 from Inverse Simulation Using Three Sidestep Profiles

The use of an order 5 polynomial to describe the transient in the acceleration equation (5) in place of the cubic of equation (4) while keeping the defining parameters t_a and $\dot{V}_{max}$ constant gives increased quickness values. This effect is to be expected in view of the increase in the peak value of the slope of the acceleration during the transient phase shown in Figure 5. If allowance is made for this difference between the two descriptions there is little to choose between the two profiles. In fact if the quickness is deliberately increased by reducing t_a then the lateral cyclic control limit is eventually reached in such a way that the limiting quickness values are identical. In the sections to follow, the results have been obtained from the 5th order profile of equation (5).

3.5 Influence of Configuration

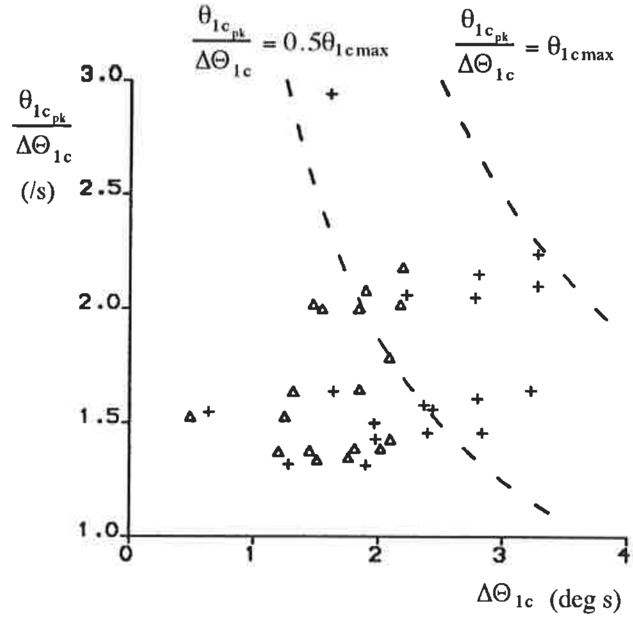
Now consider the effect of altering the helicopter's configuration to a less agile version. The Helicopter 2 configuration of the vehicle has more weight and significantly reduced rotor stiffness. Applying the same manoeuvre to it produces, as seen in Figure 13, almost identical attitude quickness values - in fact occurring in closely positioned pairs.



▲ Helicopter 1
+ Helicopter 2

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

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. However, there is the requirement that the helicopter must be capable of performing the defined manoeuvre. As the severity of the manoeuvre increases and the quickness values rise, a less capable helicopter will reach a limiting situation in, for example, its lateral cyclic control. Therefore, the limiting value of the attitude quickness parameter may be used to distinguish between the performance of two candidate helicopters. The current study is, however, directed towards handling qualities and the control quickness introduced in section 3.2 is significantly influenced by variations in configuration. Figure 14 shows quite clearly the different distribution of points on the control quickness chart produced by the two configurations. The difference represents the additional effort required by the pilot to drive the inferior configuration through the same manoeuvre.



▲ Helicopter 1
+ Helicopter 2

Figure 14 Lateral Cyclic Quickness Chart for 2 Configurations from Inverse Simulation of Rapid Sidestep MTE

The control quickness parameter, as defined in Section 3.2, is remarkably effective in discriminating between different configurations. Also marked on Figure 14 are the contours corresponding to 50% and 100% of the lateral cyclic control limit $\theta_{1c_{max}}$. It can be seen that points for Helicopter 2 tend to approach closer to this limit than the points for Helicopter 1. The potential of a quickness chart approach for conveying the handling qualities aspects of the results of inverse simulation has been demonstrated. A useful measure of handling is the rate of occurrence of control activity close to the available limit so the information of Figure 14 may be expressed in the more revealing form of Figure 15 which compares the frequency of control quickness values as a percentage of $\theta_{1c_{max}}$ for the two configurations. The distinction between the two configurations is quite clearly conveyed by this diagram and unambiguously identifies Helicopter 2 as the inferior configuration.

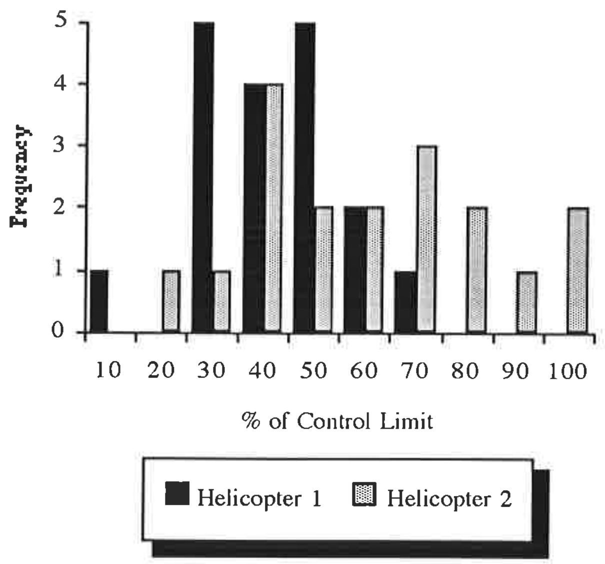


Figure 15 Lateral Cyclic Qickness Frequency Chart for Rapid Sidestep

3.6 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. The distribution of points on the control quickness charts may be used as a comparative measure of handling qualities. The frequency of occurrence of quickness values close to the control limit of each helicopter gives a clear indication of their relative handling qualities.

4. Conclusions

The use of attitude and control quickness parameters in a dual relationship promises useful exploitation in the objective assessment of handling qualities by inverse simulation.

Two preliminary conclusions may be made in this context.

(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 property of forcing Level 1 behaviour 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 refinement, 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 two conditions set out in the introduction are sufficient of the successful use of inverse simulation - providing it is realised that it is the control, rather than attitude, quickness that is the determining measure in the assessment.

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