Pilot Modelling and Inverse Simulation for Initial Handling Qualities Assessment

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ABSTRACT

This paper describes the development of an approach to handling qualities investigation that can be applied at an early stage in the design of the vehicle. It makes use of inverse simulation techniques, together with a pilot model to provide an integrated description of the man-machine control system. In order to incorporate pilot effects into data generated by inverse simulation, the output from an inverse simulation run is applied as input to a closed-loop system model that includes the vehicle dynamics and a simple parametric model of the pilot. Parameters of the pilot model are determined by optimisation and the pilot effect is added to the system output. Validation of the approach is achieved through a case study involving a predefined mission task involving a lateral manoeuvre. Equalisation characteristics estimated for each pilot are compared with those found by inverse simulation for the same manoeuvre. This approach may be applied using a simple real-time simulation on a desk-top computer and could be of value in identifying any potential deficiencies in a helicopter flight control system at an early stage in its development.

Nomenclature

$e^{-\tau s}$	pure time delay
p_{pk}	peak roll rate
p, q, r	linear roll, pitch and yaw rates
u, v, w	linear aircraft velocity components
K_P	human operator gain
Q_p	pilot attack
Q_ϕ	roll attitude quickness
T_i	lag time constant
T_l	lead time constant
T_n	neuromuscular time delay
$Y_P(s)$	helicopter pilot transfer function
ϕ, θ, ψ	linear roll, pitch and yaw attitudes
$\dot{\eta}_{pk}$	peak stick displacement derivative between zero crossings
θ_{0tr}	linear tail rotor collective pitch angle
θ_{1c}	linear lateral cyclic
$\Delta\phi$	change in roll attitude between zero crossings
$\Delta\eta$	change in net stick displacement between zero crossings
ADS	Aeronautical Design Standard
AFCS	automatic flight control system
HEC	Human Equalisation Characteristics
Helinv	helicopter inverse simulation
HGS	helicopter generic simulation
HQR	handling qualities ratings
MMCS	Man Machine Control System
MTE	mission task element
PPM	Precision Pilot Model

Introduction

Designing and performing sets of handling qualities experiments on a full-scale flight simulator facility to evaluate design options at an early stage can be expensive in terms of cost and time. In this work, two simulation approaches have been applied to an initial handling qualities assessment. The first of these is conventional forward real-time simulation involving calculation of the helicopter open-loop or closed-loop response to a set of control inputs. The second is inverse simulation (Ref. 1) through which the user derives the state variable and control input time histories needed to follow a predefined flight path. Although human-operator characteristics are clearly incorporated in any piloted real-time simulation results, pilot effects are not integrated into inverse simulations. To replicate the man-machine system using inverse simulation the pilot effect must be integrated into the recorded data.

The complete man-machine control system involved in handling qualities studies is inherently non-linear and thus difficult to model. Early work by Tustin (Ref. 2), as summarised by Wilde and Westcott (Ref. 3).

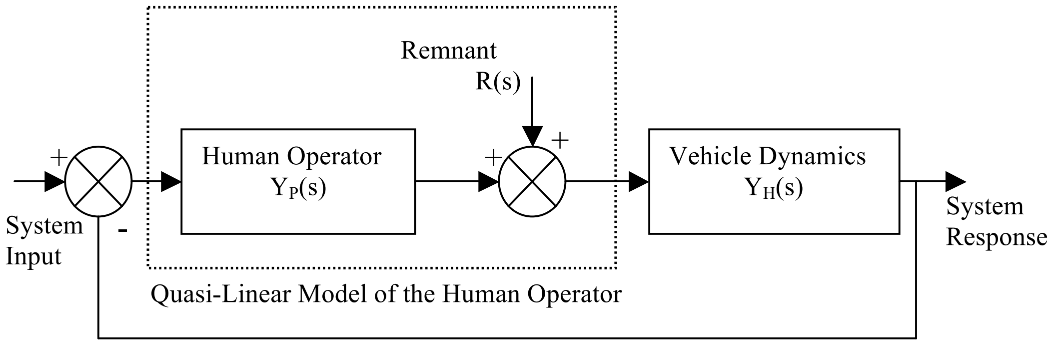

Figure 1. A Quasi-Linear Model of the Human Operator

Pilot models

stemmed from the observation that many non-linear systems have responses to simple control inputs that are similar to the responses of an equivalent linear system plus remnant as demonstrated in Figure 1. One of the most widely applied models is the so-called Precision Pilot Model (PPM) that was developed from early work by Tustin (Ref. 2) and reviewed by McReur and Krendel (Ref. 4) and can be described by the transfer function

$$Y_p(s) = K_p \frac{(1 + T_l s)}{(1 + T_i s)} \left\{ \frac{e^{-\tau s}}{1 + T_n s} \right\} \qquad (1)$$

where K_p is the *'Pilot Gain'* representing the pilot's ability to respond to an error in the magnitude of a controlled variable, T_l is the *'Lead Time Constant'* reflecting the pilot's ability to predict a control input and T_i is the *'Lag Time Constant'* which describes the ease with which the pilot generates the required input. These three parameters are known collectively as the *'Human Equalisation Characteristics'* (HEC).

The remaining two terms within the transfer function can be defined as the *'Inherent Human Limitations'* where $e^{-\tau s}$ represents a pure time delay describing the period between the decision to change a control input and the change starting to occur. Finally T_n is the *'Neuromuscular Lag Time Constant'* which represents the time constant associated with contraction of the muscles through which the control input is applied by the pilot. These human limitation parameters may be assumed constant for a given pilot flying a single-axis tracking task (Ref. 5 & 6), leaving the equalisation parameters as the factors of particular interest in the assessment of pilot performance.

In cases where the mission task is only a few seconds in duration and the manoeuvre involves small changes of vehicle attitude it may be possible to consider the vehicle dynamics as being linear. This means that the pilot characteristics can be assumed to be constant for the manoeuvre and the PPM is an appropriate type of description. This type of pilot model has been adopted for the work described in this paper because the mission task duration and chosen manoeuvre characteristics meet the requirements. A fixed value of 0.1sec has been chosen for the neuromuscular lag time constant (Ref. 5) and although the pure time delay parameter has been found to vary depending upon the tracking task being assessed, values of the order of 0.1 sec have been found to be appropriate. The delay has been modelled using a fourth-order Padé approximation.

Inverse simulation methods and manoeuvre modelling

The inverse simulation package Helinv, developed at the University of Glasgow by Thomson and Bradley (Ref. 1), can be used to predict a set of control inputs required to force a vehicle along a predefined flight path. By defining a given mission task in suitable algebraic form, the Helinv algorithm solves the equations of motion generating a unique time history of control inputs to allow that task to be flown. Helinv incorporates a helicopter model which is known as the Helicopter Generic Simulation (HGS) (Ref. 1). Although the Helinv algorithm can be used in conjunction with the nonlinear HGS vehicle model, most of the work described in this paper was based on the linearised vehicle description

$$\dot{\underline{x}} = \mathbf{A}\underline{x} + \mathbf{B}\underline{u} \qquad (2)$$

where the state and control vectors respectively are typically

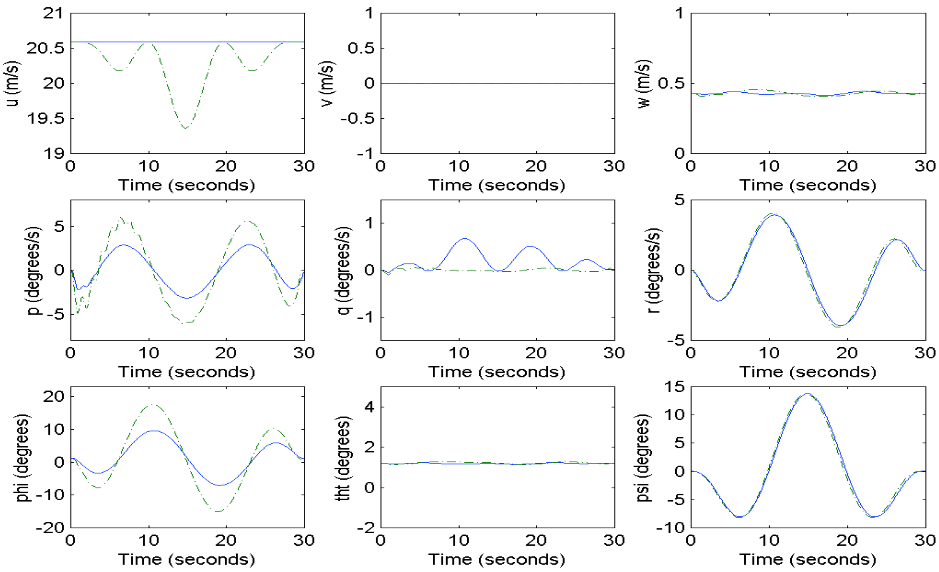

Figure 2. Comparison of Helinv and Linear Helinv Predicted State Parameter Time Histories for 40 Knot Slalom with Constrained Side slip

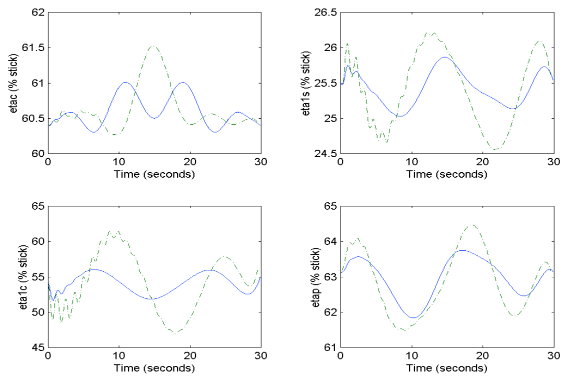

Figure 3. Comparison of Helinv and Linear Helinv Predicted State Parameter Time Histories for 40 Knot Slalom with Constrained Side slip

$$\underline{x} = \begin{bmatrix} u & v & w & p & q & r & \phi & \theta & \psi \end{bmatrix}^T \quad (3)$$

$$\underline{u} = [\theta_0 \;\; \theta_{1s} \;\; \theta_{1c} \;\; \theta_{0tr}] \quad (4)$$

The successful application of Helinv depends on the mission task model being representative of the actual task to be flown. A library of mission task elements exists in the form of the Aeronautical Design Standard ADS-33D (Ref. 7) published by the U.S. Army. The document suggests guidelines for performing single-axis tracking tasks that can be applied to the development of a manoeuvre mathematical model.

Figures 2 and 3 present a comparison of the nonlinear and linearised Helinv state and control variable time histories for the 40 knot constrained side slip manoeuvre with data for a Puma helicopter. Analysis of these plots shows that although the linear inverse simulation technique requires a greater roll angle (ϕ) and greater values of all the control inputs, the linear inverse simulation provides a close approximation to the results found from the full non-linear algorithm in this particular case.

As Helinv 'flies' the manoeuvre precisely (that is without deviation from the defined trajectory), the control time histories generated can be considered as being from the 'perfect pilot'. When this is used as the command signal for the MMCS, the PPM will minimise the error by calculating the optimum HEC. Other methods for obtaining manoeuvre flight data are required in order to compare with those generated from Helinv. Ideally, real flight data would be used but an alternative is to make use of a simulator facility.

Helicopter Handling Qualities Assessment

The US Army Aeronautical Design Standard (Ref. 7) defines a range of mission task elements (MTEs) that can be used to assess helicopter handling qualities and to verify that the task is flown in such a way that qualitative handling qualities assessment can be carried out. This latter requirement involves the 'attitude quickness' parameter which defines the behaviour of the helicopter in the pitch, roll and yaw axes. For example, when applied to the roll axis, the roll quickness parameter is defined by

$$Roll\ Quickness = Q_\phi = \frac{p_{pk}}{\Delta\phi} \quad (5)$$

where p_{pk} is the peak roll rate encountered and $\Delta\phi$ is the coincident change in roll attitude occurring between zero crossings.

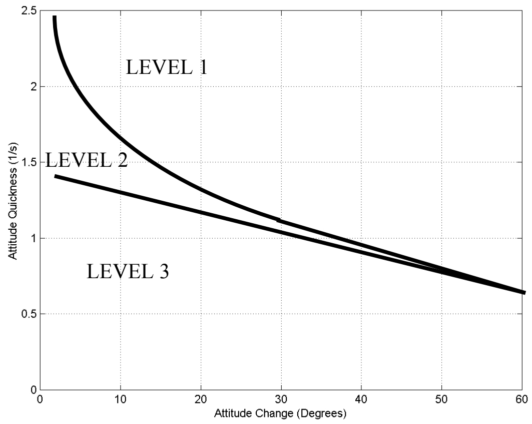

Figure 4. Roll Attitude Quickness, Tracking.

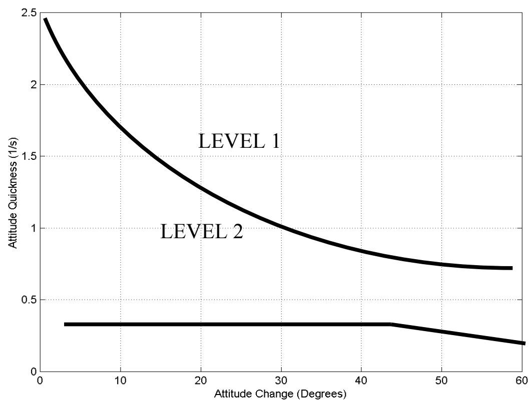

Figure 5. Roll Attitude Quickness Chart, All Other MTEs

Figures 4 and 5 show how the roll attitude quickness parameter can be plotted against the minimum attitude change to ascertain the handling qualities level for a particular flight manoeuvre. In such diagrams Level 1 indicates adequate control performance while Level 2 is acceptable only in emergency situations.

Pilot workload can be measured by a parameter called ‘pilot attack’, as described in (Ref. 7), which is calculated in a similar way to the attitude quickness parameter. In this case the focus is on the pilot stick displacement instead of roll attitude. This parameter can be defined as

$$Pilot\ Attack\ (Q_p) = \frac{\dot{\eta}_{pk}}{\Delta\eta} \quad (6)$$

where $d\eta_{pk}/dt$ is the peak value of the rate of change of stick displacement between zero crossings and $\Delta\eta$ is the corresponding change in the net stick displacement. Each stick displacement can be viewed as an element of pilot workload identifiable by associating an attack parameter with each peak or trough. Upon analysis of the stick displacement time history, it is evident that the pilot action is characterised by a maximum stick rate and a corresponding stick displacement, allowing the calculation of a pilot attack parameter.

Padfield & Jones et al (Ref. 8) stipulate that the attack parameters representing a large net stick displacement are associated with vehicle navigation while the parameters with a small stick displacement and small attack describe stabilisation. Finally, cases with small stick displacement and high attack parameters are related to the control inputs for guidance through the task.

Development of a mission-programmable real-time flight simulator

Although there are many personal computer (PC) based flight simulator programs available commercially, one that allowed access to the program source code in order to change the environment, the task and the vehicle model was not on the market. Therefore, a mission programmable flight simulator based on a PC was developed.

Central to the real-time simulator is a helicopter model describing the vehicle response to a control input. Attitude change and distance travelled by the helicopter are calculated and then used to manipulate the visual environment.

The chosen model is the linearised six-degree-of freedom HGS model in state-variable form with the state and control vectors calculated at a reference trim state.

The control inputs necessary to vary the vehicle state variables are applied through a three-axis ‘Flightstick’ joystick. Longitudinal and lateral cyclic inputs are controlled by stick position. The z-axis, which is a dial, can be assigned to control either the main or tail rotor collective directly or through the AFCS. Although this three axis joystick cannot fully simulate the four helicopter control inputs this was not an issue for the selected mission tasks involving either longitudinal or lateral tracking with a reduced order model.

Reduced-order modelling of the vehicle dynamics for the lateral jink task

Although the helicopter model incorporated in the flight simulator described above is linear it is still difficult to pilot due to the complex cross-coupling of the helicopter modes. Employing a reduced order model instead of the full system, by removing some of the cross-coupling terms, can alleviate the situation and reduce the workload. This was particularly important in providing a computer-based environment within which the concept of using inverse simulation in conjunction with a pilot model could be investigated.

The reduced-order model for the manoeuvre must be dynamically representative of the full linear system or the reduced model is invalid. Clearly, the same reduced-order model cannot be applied to different manoeuvres because each will have different dominant state variables and a unique reduced order model must be derived for each case.

In order to obtain meaningful results from a handling qualities analysis, a manoeuvre that portrays Level 1 handling characteristics must first be defined in accordance with the ADS-33 recommendations. The approach adopted in selecting the task took due consideration of the fact that the helicopter model employed in the flight simulator is linear and is a valid representation of the vehicle only for small perturbations from trim and thus for short periods of time.

The manoeuvre chosen for the present study is the 'lateral jink'. This is a shortened form of the ADS-33 slalom task, constructed for use with the linear Helinv model. In terms of a polynomial description the flight path can be defined by a fifth order polynomial to give the flight path defined by the continuous line in Figure 6. The task can also be defined by a piecewise representation of the aircraft's lateral velocity. The maximum lateral velocity attained in the task is defined such that when integrated to give the flight path, the maximum lateral displacement has the required value. The piecewise flight path is shown by the dashed line in Figure 6.

An apparent advantage of the piecewise definition over the direct definition of the flight-path is that if the task does not yield Level 1 handling qualities, the time required to achieve the maximum or minimum acceleration, velocity or displacement (depending on how the task is defined) can be altered to make the manoeuvre more or less aggressive.

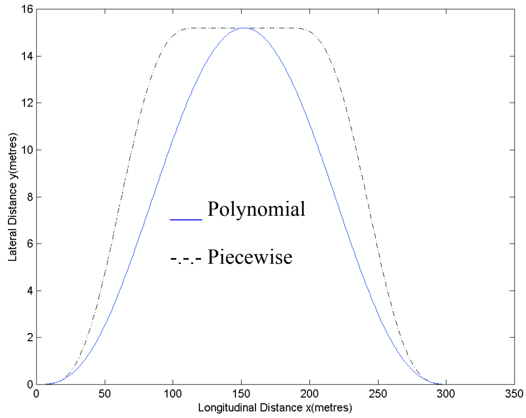

Figure 6. Piecewise and Polynomial Defined Lateral Jink Flight Paths

Since the lateral jink is primarily a lateral tracking task, the reduced order model involves only four state variables and two control inputs

$$\boldsymbol{x} = [\, v \quad p \quad r \quad \phi \,]^{\mathrm{T}}$$

$$\boldsymbol{u} = [\, \theta_{1c} \quad \theta_{0tr} \,]^{\mathrm{T}}$$

Figure 7 compares the four state variables and two control time histories for the reduced order model with the full linear model for the lateral jink manoeuvre. The state variable time histories of the reduced model compare closely with those of the full-order model, although there is a slight change in the control strategy due to two of the control inputs being constrained. It was also found that when the reduced-order roll angle time history was applied as the command signal for the MMCS, human equalisation characteristic parameters similar to those calculated using the full linear model were obtained.

The lateral jink task has been represented in the flight simulator by a series of gates representing the start and finish of the task and where the maximum lateral translation occurs. The flight path defined by the polynomial equation is also plotted in the simulator, such that the start and end of the flight path line coincide with the start and finishing gates, respectively, as shown in Figure 8.

The maximum lateral distance is then achieved at the middle of the gate representing the maximum lateral distance. The three gates are each two metres wide, representing the maximum tolerable flight path deviation at these points. The pilot attempts to fly the task by following the manoeuvre flight path.

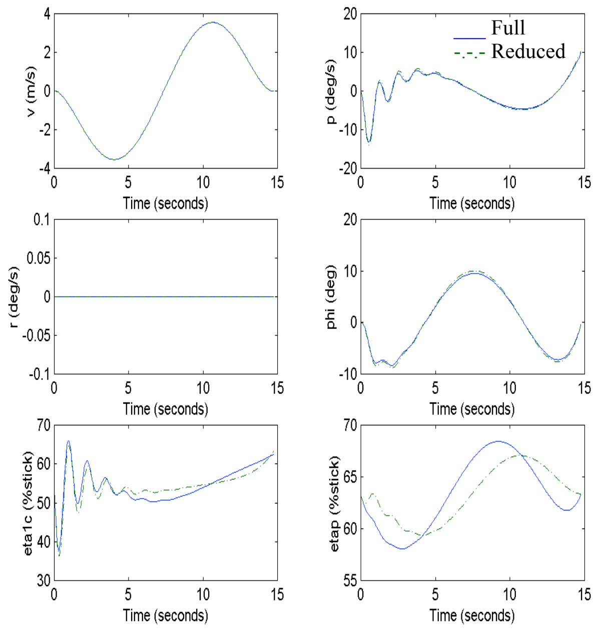

Figure 7. Comparison of Full and Reduced Order Lateral Jink State and Control Time Histories

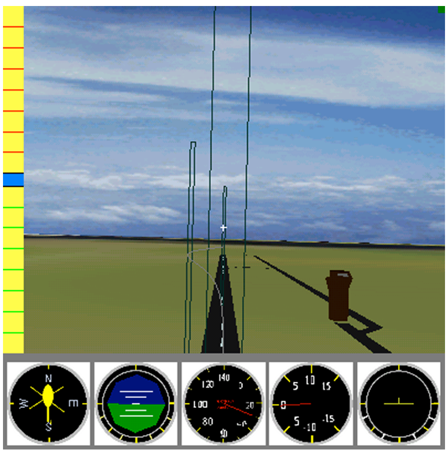

Figure 8. Mission Task Flight Path Representation in the Flight Simulator

Estimation of parameters of the pilot model for the lateral jink manoeuvre

The state and control time histories derived using the inverse algorithm represent the ideal state and control time histories for a given task. This is because the command signal generated by this technique takes no account of human operator limitations. The human equalisation characteristics (HEC) derived from the PPM for a Helinv-generated command signal represent the optimum achievable HEC for that task, when performed by the human operator.

The optimisation technique for estimation of parameters of the HEC is a form of constrained optimisation, known as Sequential Quadratic Programming (Ref. 9) and implemented in Matlab®. The optimum HEC gives the minimum mean square error between the system input and the system response.

The polynomial form of the lateral jink manoeuvre has been found to give equalisation parameters that are well within the expected range of human operator parameters given by McRuer and Krendell (Ref. 4). This was not found to be the case for the piecewise lateral jink which required a lead time constant at the upper limit of the range due to the highly aggressive nature of this task at 40 knots in a Puma helicopter. Although the global polynomial lateral jink task does not exhibit Level 1 HQR for all attitude quickness parameters it does allow the approach to be evaluated without invalidating the assumptions of linearity. Given a nonlinear real-time simulation facility and use of the nonlinear Helinv algorithm, manoeuvres such as the piecewise lateral jink and slalom could be considered using an identical approach.

During the estimation of HEC for the lateral jink manoeuvre the roll angle time history obtained from Helinv is applied as the command signal for the MMCS as shown in Figure 1. This gives the output from the system which has the pilot effect on the command signal added and the corresponding roll rate can be found from this by differentiation, as shown in Figure 9. It is clear from these plots that the pilot model has introduced an additional time lag into the Helinv data, which is larger at the start of the task than in the middle and end sections. Figure 10 compares roll attitude quickness parameters generated using Helinv with the output from the MMCS for the same case.

The effect of the pilot limitations on the roll angle is evident, resulting either in a reduction in the net roll angle or a decrease in the attitude for the important 'navigation' quickness parameters. There is some discrepancy between the guidance parameters towards the top left of the diagram and this can be explained by differences of strategy adopted at the start of the task. The results suggest that although the main navigation quickness ratings for this task have remained approximately the same, smaller changes of roll angle are required by the pilot to achieve them due to the delay introduced at the beginning of the task.

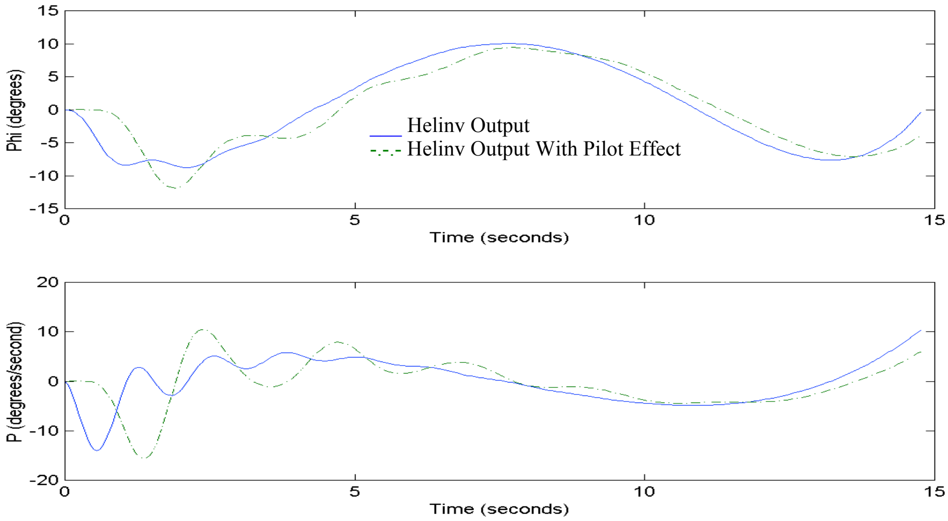

Figure 9. Helinv derived State Output with Added Pilot Effect

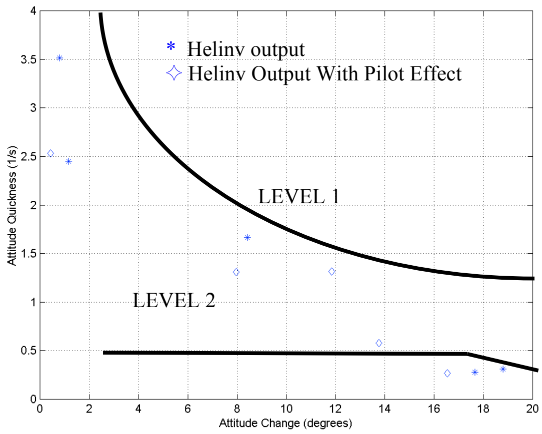

Figure 10

Multiple axis tracking

Although the lateral jink, like the ADS-33D defined slalom task, can be described as a single-axis tracking task, the operator is still required to apply more than one control input due to the cross-coupling between the longitudinal and lateral axes of the helicopter. The two control inputs required to perform the lateral jink task were considered in the previous section where pilot attack charts could be plotted separately for both controls. If the task is to be flown with two controls there is an issue concerning the determination of the HEC. The problem is that the command signal, in this case the roll angle, is optimised with respect to the control input that causes the change in the state variables. The transfer function representation of the vehicle dynamics is also derived from this relationship and as two inputs are applied for this task, two optimisations are needed. The first relates the roll angle to lateral cyclic input and the second roll angle to tail rotor collective input. The resulting equalisation characteristics will clearly have different pilot gains and lead times for the different axes because, although both inputs contribute significantly to the vehicle control they are applied with different strategies. However, in order to analyse the overall task, it is necessary to model the helicopter in such a way that only one set of HEC is produced. In order to represent multiple control inputs in the linear MMCS a minimum of two transfer functions are required in parallel and the vehicle dynamics block of the MMCS must be modified accordingly.

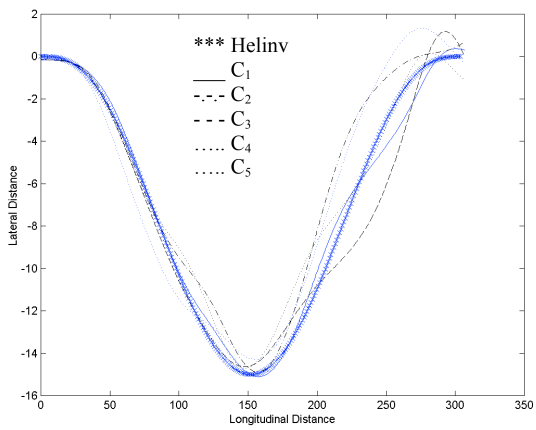

Figure 11. Recorded Flight Path For Helinv and The Series of Flights Performed by Pilot C

Results for the reduced-order helicopter model performing the lateral jink task

In order to verify that the inverse algorithm with additional pilot effect is accurate, a series of experiments were devised utilising the flight simulator and the described lateral jink task, allowing a comparison between the model and real pilots. Three human operators who could offer varying degrees of experience took part in the experiments. Pilot A was the least experienced operator. The results listed for Pilot B and Pilot C were actually recorded from the same subject, but the results shown for Pilot C were for the cases were the operator concerned had accumulated a great deal more experience than for those shown as Pilot B. Pilot D was the most experienced operator. Each pilot was required to fly the single axis lateral jink manoeuvre in the flight simulator at 30, 40 and 50 knots. Each pilot carried out the task a minimum of five times for each flight speed.

Results from studies using Helinv show that it is possible to perform this single axis tracking task, as defined in the simulator, using only lateral cyclic control input or tail rotor collective input alone or a combination of the two. Clearly, if the pilot adopts a control strategy that differs greatly from the optimal inverse simulation (ie the pilot uses predominantly one control) the results will not be comparable. Throughout the work in hand the task was flown in the flight simulator using a combination of lateral cyclic and tail rotor collective inputs.

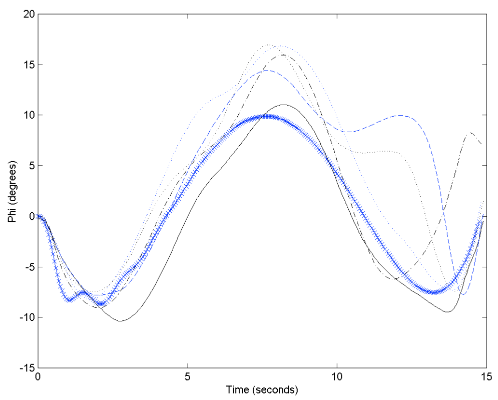

Figure 12. Roll Angle Time Histories For Helinv and The Series of Flights Performed by Pilot C

The state and control time histories were recorded for each series of flights for all pilots throughout the prescribed range of flight speeds. The recorded roll angle time histories were then applied as the command signal to the MMCS to allow estimation of the pilot equalisation characteristics required. Typical results are presented in Table 1 for the series of flights performed by Pilot C at 40 knots. The corresponding flight paths are recorded in Figure 11 and the roll angle time histories in Figure 12.

Flight	*Error*	*Gain*	*Lead*	*Lag*
Helinv	*8.888*	*0.129*	*0.771*	*0.1*
C_1	*7.998*	*0.1674*	*0.654*	*0.1*
C_2	*9.896*	*0.152*	*0.762*	*0.1*
C_3	*12.293*	*0.126*	*1.099*	*0.1*
C_4	*10.686*	*0.11*	*1.279*	*0.1*
C_5	*9.766*	*0.14*	*0.968*	*0.1*

Table 1

The results for Pilot C, who was relatively experienced in piloting the task, all show values of error that are similar in magnitude for different runs and the corresponding gain and lead parameters for the PPM are also fairly consistent throughout the runs. The roll angle time history in Figure 12 shows that, for flight C_1, a large time lag has been introduced in the first half of the task but this is not evident later in the flight. The remaining attempts (C_2 to C_5) all show similar flight paths and roll angle time histories for the first half of the manoeuvre, where a large roll angle is required to reach the maximum lateral displacement, but employ differing strategies in the second half of each flight. This is clear from Figure 12 where, after the middle gate turn for C_3 and C_4, the pilot rolls back too early and then attempts to correct this by slowing the roll rate reversal, resulting in high lead times. The roll angle and roll rate time histories recorded from each task can be subjected to a handling qualities assessment in terms of attitude quickness parameters using an attitude quickness chart as illustrated in Figure 13.

It is evident from this graph that each time pilot C flew the task, quickness parameters requiring larger attitude changes than those calculated for Helinv are recorded at the start of the task. This contrasts with the 'Helinv plus pilot effect' parameters shown in Figure 13 but all other parameters follow the predicted pattern.

The averaged gain, lead and lag times were then found for each series of flights for each pilot and are presented in Tables 2, 3 and 4.

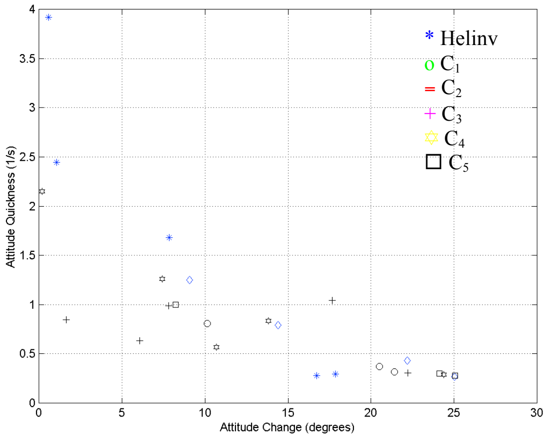

Figure 13. Attitude Quickness Charts for the Series of Flights Performed by Pilot C

Pilot	*Error*	*Gain*	*Lead*	*Lag*
Helinv	*3.397*	*0.138*	*0.578*	*0.1*
A	*9.645*	*0.151*	*0.825*	*0.1*
B	*8.263*	*0.136*	*0.676*	*0.1*
C	*6.606*	*0.146*	*0.636*	*0.1*
D	*7.638*	*0.147*	*0.629*	*0.1*

Table 2 30 Knot HEC

Pilot	*Error*	*Gain*	*Lead*	*Lag*
Helinv	*11.35*	*0.132*	*0.598*	*0.1*
A	*8.804*	*0.181*	*0.517*	*0.1*
B	*17.75*	*0.139*	*0.738*	*0.1*
C	*12.26*	*0.143*	*0.756*	*0.1*
D	*11.74*	*0.155*	*0.689*	*0.1*

Table 3 40Knot HEC

Pilot	*Error*	*Gain*	*Lead*	*Lag*
Helinv	*32.87*	*0.120*	*0.684*	*0.1*
A	*15.49*	*0.174*	*0.551*	*0.1*
B	*28.66*	*0.158*	*0.529*	*0.1*
C	*24.83*	*0.149*	*0.661*	*0.1*
D	*21.08*	*0.135*	*0.706*	*0.1*

Table 4 50Knot HEC

It can be argued that the HEC parameters derived using inverse simulation are optimal. Hence the human operator gain should not exceed the Helinv gain, the lead time constant should not be smaller than that generated from inverse simulation and the pilot error should be greater than that obtained with Helinv. All the average pilot lead times for the 30 knot case are consistent with this statement and the corresponding gains are similar to those calculated from Helinv. For 40 knots the same is true for pilots B, C and D but gains and lead times for pilot A (the least experienced pilot) clearly do not fit the previous statement. It appears that this pilot adopted a strategy that differed significantly from Helinv and with an error value and lead time at 30 knots which are higher than those recorded for any other operator did struggle to perform the task. However, at 40 and 50 knots pilot A shows gains that are significantly larger than the corresponding values for the other pilots and lead times that are significantly smaller. This suggests that instead of finding the task increasingly difficult to perform, pilot A had a preferred or optimal flight speed somewhere in the region of 40 knots. Pilot D displays similar characteristics.

The results for pilots C and B (the same operator with different experience levels) suggest that pilot C, with more experience, has a lower error than pilot B. Comparison of the gains calculated for these two pilots also reveals that throughout the flight speed range the gains are very similar. The gain of pilot B (inexperienced pilot C) increases with flight speed but with more experience (as pilot C) the gains remain similar throughout the speed range. It is also clear from the tables that as flight speed increases the error increases in general . This is not surprising since at higher speed the pilot has less time and is less able to respond to an error in the controlled variable.

It is interesting to note that the lag time constant values in Tables 2 to 4 show that this parameter has tended to the minimum boundary in every case. This is simply because the operator has applied the control inputs with a smooth transition leading to smooth roll angle time histories. In a more vigorous manoeuvre, such as the piecewise lateral jink, larger lag time constants are introduced.

Since handling qualities assessments in terms of attitude quickness and pilot attack analysis cannot be carried out from averaged time history data for a series of flights, it was decided to carry out this type of assessment for the flight case having pilot equalisation characteristics (for a single axis analysis) closest to the average for each pilot.

Figure 14 shows the 40 knot attitude quickness charts for the three speeds for the different pilots, together with the results generated from Helinv. The first noticeable result from Figure 14 is the presence of the Helinv parameter in the top left corner of the chart. This attitude quickness parameter is due to a transient oscillation in the roll rate and is believed to be a feature of the linear model. This oscillation corresponds to a very small change in the roll angle and thus gives an uncharacteristically large attitude quickness parameter.

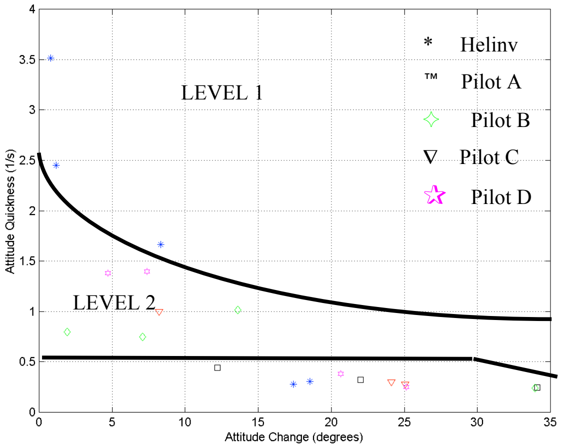

Figure 14. 40 Knot Attitude Quickness Chart

Further examination of Figure 14 reveals that there are three distinguishable parameter groupings, each representing attitude quickness parameters for pilots B, C and D. The first grouping is in the bottom left hand corner of the chart and relates to small changes of attitude. The second grouping defines slightly larger attitude changes between 5 and 10 degrees, while the third group appears in the bottom right of the chart and can be associated with larger of faster control inputs where attitude changes are greater than 15 degrees. It is interesting to note that all the quickness parameters in each of the three groupings, for these three pilots, have approximately the same value. This suggests that the human operators piloted the task in a similar manner and that the recorded time histories are satisfactory for use in a handling qualities analysis. Pilot A, who has already been shown to adopt a different control strategy, does not fit into this characterisation. He has quickness parameters that fit into the second and third groupings but has none in the first set because larger roll angles are recorded throughout the task in his case.

For the 30 and 50 knot cases, the attitude quickness parameters for the four pilots fall into similar categories, suggesting that these mission task elements are again suitable for a handling qualities assessment. Comparison of the three quickness charts also demonstrated that as the flight speed increases the required roll attitude also increases for all the pilots. A noticeable feature of this increased attitude change is that the attitude quickness parameters have not increased, but remain approximately the same. This is because, as the flight speed increases, the mission time decreases. Therefore the required roll attitude change becomes larger and faster while the ratio of roll attitude to roll rate remains much the same. It should be noted again that these results do not meet Level 1 handling quality requirements as specified by ADS-33D. They only pass the attitude quickness assessment due to constraints on the task definition as previously discussed.

The pilot attack parameter can be calculated separately for lateral cyclic and tail rotor collective inputs. The analysis has been performed at 40 knots for the reduced order linear simulation result, for the task closest to the average for each pilot and also for each case for pilot C.

Figure 15 shows the lateral stick displacement and its derivative for the Helinv case, together with results for pilot B, while Figure 17 shows the corresponding lateral cyclic attack chart for the task closest to the average for each pilot. This shows that no pilot applied large stick displacements suggesting that the helicopter is guided through the task, rather than being navigated.

Since the task requires two control inputs, the attack parameters relating to the tail rotor collective have also been included. Figure 16 shows the tail rotor collective displacement and its derivative while Figure 18 displays the corresponding tail rotor attack chart for the five cases performed by pilot C. Figure 18 shows the attack parameters for the task closest to the average for each pilot. One point to make about these results is that a problem with the tail rotor control axis of the flight simulator did not allow a smooth transition when tail rotor input was increased or decreased, resulting in some artefacts which are not a feature of the real system. These have been removed from the attack chart which shows attack parameters for the tail rotor collective input that are of the same order of magnitude as those in the lateral cyclic attack chart. This confirms that each control input influences the state time histories to the same extent and that no one control dominates the task.

Conclusions

The results presented in this paper demonstrate that in principle inverse simulation methods and a simple desk-top helicopter flight simulator can be used to generate simulated

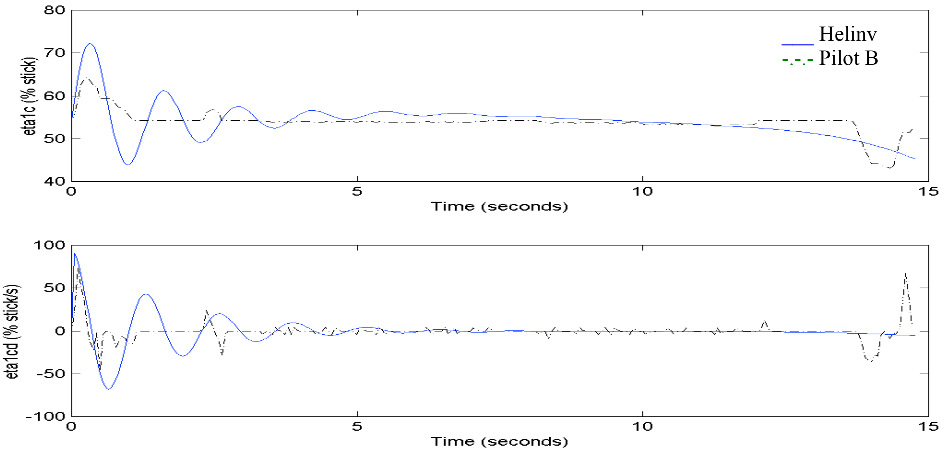

Figure 15. 40 Knot Helinv and Pilot B Lateral Stick Displacement and Derivative

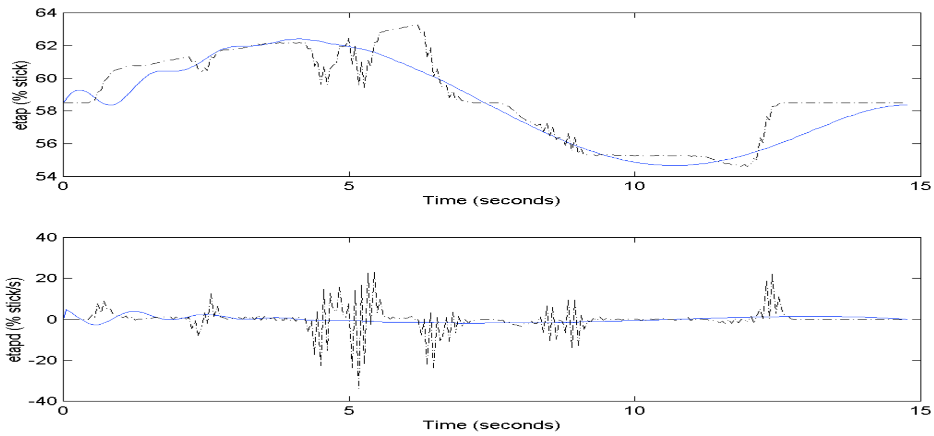

Figure 16. 40 Knot Helinv and Pilot B Tail Rotor Collective and Derivative

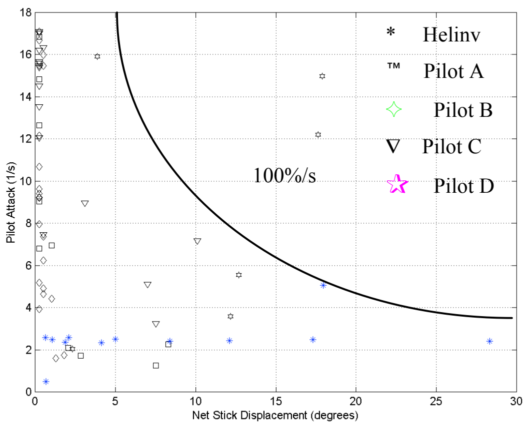

Figure 17. 40 Knot Lateral Cyclic Pilot Attack Chart

flight data at an early stage in the design of a new vehicle for use in handling qualities investigations. Although the current investigation has been based mainly on linearised descriptions of the helicopter and a relatively simple pilot model, the principles of

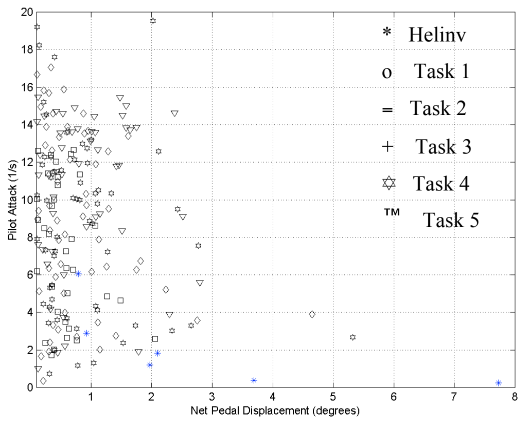

Figure 18. 40 Knot Tail Rotor Collective Pilot Attack Chart

the approach apply equally well to non-linear vehicle models and to other forms of pilot model.

With pilot effect being incorporated into the output of an inverse simulation it is possible to include human operator characteristics within an inverse simulation to improve model fidelity. It is shown that optimum equalisation characteristics for each pilot can be related to the corresponding attitude quickness and attack charts. The inclusion of pilot effect within the simulation models increases overall model fidelity and provides a new and potentially useful design tool.

The man-machine control system with the precision pilot model has been used to relate the primary controlled variable to two control inputs. Further analysis of multiple axis pilot modelling to determine pilot characteristics for the task incorporating the full vehicle state matrix rather than just the primary controlled variable.

The work could readily be extended using a nonlinear helicopter model with four control inputs. This paper considers only one lateral task but many other tasks have been defined in the Helinv algorithm and these could also be flown in a modified version of the flight simulator. A handling qualities assessment on the corresponding test data would then allow a catalogue to be established of pilot ability and vehicle handling qualities over a range of mission tasks and flight speeds.

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