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ESTIMATION OF PILOT MODEL PARAMETERS FOR HELICOPTER HANDLING QUALITIES STUDIES

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Abstract

A collaborative programme of research into helicopter handling qualities and mission effectiveness is currently underway in the UK, involving the Defence Evaluation and Research Agency, Glasgow Caledonian University and the University of Glasgow. This paper presents one contributing element to the programme, carried out at the University of Glasgow. The practice of using mathematical models to simulate pilot behaviour in one-axis stabilisation tasks is a well known conventional simulation problem. In this paper an accepted mathematical model of a pilot is used as the controller of a rudimentary helicopter model. Test manoeuvre data from inverse simulation is used to provide time-histories for forcing functions to the pilot/helicopter system, and a constrained optimisation routine is utilised to obtain values for the pilot gain and lead/lag equalisation parameters. It will be shown that as the theoretical pilot is required to 'fly' different manoeuvres, or indeed if the level of manoeuvre aggression is varied, the 'pilot' adjusts these parameters to perform a tracking task in compensatory control. The paper considers initially the pilot and helicopter models and subsequently analyses the whole system, illustrating how the pilot model changes with different situations.

Nomenclature

A	state matrix of helicopter	
B	control matrix of helicopter	
e	error function	
K_P	pilot gain	
P, Q, R	helicopter angular velocity components	(deg/s)
Q_E	output torque of the engines	(Nm)
T_I	lag time constant	(s)
T_L	lead time constant	(s)
T_N	neuromuscular lag time constant	(s)
U, V, W	translational velocity components of helicopter centre of gravity	(m/s)
$\underline{u}$	control vector	
$\underline{x}$	state vector of system	
$\underline{y}$	output vector from system	
$Y_A(s)$	aircraft actuator transfer function	
$Y_H(s)$	helicopter transfer function	
$Y_P(s)$	pilot transfer function	
θ_0	main rotor collective pitch angle	(deg)
θ_{1s} , θ_{1c}	longitudinal and lateral cyclic pitch angles	(deg)
θ_{0tr}	tail rotor collective pitch angle	(deg)
τ	pure time delay constant	(s)
ϕ, θ, ψ	aircraft attitude angles	(deg)
Ω	angular velocity of main rotor	(rad/s)

Introduction

With the growing complexity of pilot/helicopter interface systems, the need to develop increasingly intricate mathematical models of both the pilot and helicopter has become more urgent. Of equal importance though, is the ability to analyse the interaction between man and machine, the result of which has been the origin of an extensive volume of research, extending into such areas as handling qualities, flight simulation and understanding of flight test data, [1,2].

The University of Glasgow is involved in a programme of research into the assessment of helicopter handling qualities and mission effectiveness. The Defence Evaluation and Research Agency (DERA), Bedford, UK and Glasgow Caledonian University are also extensively involved in this programme. One element of work undertaken at the University of Glasgow has investigated the value of integrating the results from inverse simulation with pilot models. The intention of this paper is not to deal directly with the subject of handling qualities but to present the findings of work specifically associated with identifying appropriate pilot models. Subsequent studies will be carried out to potentially relate the results with other handling qualities work undertaken.

Traditional handling qualities specifications define the behaviour required of an aircraft but only implicitly take into account the behaviour of the pilot by setting limits in accordance with results obtained from many experiments in simulators and in actual flight conditions. It is necessary therefore to investigate further the pilot as an individual element within the aircraft and analyse aircraft dynamic response with human operator properties.

The aim of this paper is to present an alternative method of estimating the values of pilot gain and equalisation time 'constants' in a particular form of pilot model, the *Precision Model*, [3]. The model is set up in a compensatory type system where the pilot is considered as an individual quasi-linear element in a single-axis feedback control arrangement, presented with an error function. Inverse simulation is used to provide a reference signal and comparison with the pilot/helicopter system performance generates the required input error.

The inverse simulation package Helinv, developed at the University of Glasgow [4,5] calculates the pilot control inputs required for a modelled vehicle to fly a prescribed trajectory or manoeuvre. It can be considered as possessing the 'perfect pilot', (within model restrictions) and will therefore generate 'perfect pilot controls' required to fly a given trajectory. Successful application of inverse simulation requires that particular attention be paid to the appropriate definition of the flight path. Many of the manoeuvres in the existing Helinv software library are based on Mission Task Element (MTE) definitions given by ADS-33D [6], and care was taken to ensure that as many of the features as possible, described in the document, were captured in mathematical model derivations, [7]. The MTE Modelling section later in the paper elaborates this point and describes generally how a particular flight path can be mathematically formulated.

In this study several manoeuvres from the MTE library were selected to reflect translations in all three axes of the helicopter. Inverse simulation data from these manoeuvres were also obtained at three manoeuvre aggression levels to examine the variation in the pilot model parameters as the task became more demanding for the pilot. Time-histories of aircraft attitudes, and in one instance the vertical body velocity (heave velocity) were used as the reference forcing functions to the pilot/helicopter system. The subsequent error between the 'perfect inverse simulation' generated response and that achieved by the pilot/helicopter system was optimised to yield values for the pilot gain and equalisation time constants for each manoeuvre and level of aggression.

Although the method described in this paper has been applied to the Precision Model, there is no reason to assume that it could not be applied to other models or similar situations, where the rules of application of that particular pilot model are adhered to. Prime emphasis is placed upon illustrating the fact that the selected parameters within the precision model do change with different MTEs and to a lesser extent, with the level of aggression exercised in the manoeuvre.

The Precision Model is considered below followed by the system controlled element, a rudimentary helicopter model which represents single-axis helicopter flight. The analysis of the compensatory feedback system and subsequent results are presented in the final sections of the paper.

The Pilot Model

The ability to mathematically model human pilot behaviour has been a topic of research for many years with substantial contributions originating from such authors as McRuer, Krendel and Graham [8,9]. This section of the paper refers to the work of Pausder and Jordan, [10] and examines pilot-in-the-loop modelling. The Precision Model is widely recognised as a standard pilot model and has found applications in handling qualities studies, pilot rating evaluation and analysis of aircraft dynamic behaviour [3,10].

The Precision Model, like many other forms of pilot model, was developed to aid in the understanding of Handling Qualities Ratings, (HQRs) by modelling the behaviour of a human pilot as a closed-loop system element. The method employed was to monitor and model the response of a pilot carrying out a single-axis control task, such as maintaining a desired pitch or roll attitude. This was often done in a very simple manner and the model was derived by matching a describing function to the response of the operator. The Precision Model when given as a transfer function assumes the form,

$$Y_P(s) = K_P \frac{(1+T_L s)}{(1+T_I s)} \left\{ \frac{e^{-\tau s}}{1+T_N s} \right\} \qquad (1)$$

A mathematical model of this nature obviously does not take into account all of the variables concerned with piloting a helicopter, but it does encompass the more important and relevant features when applied to single-axis control tasks, and also has the advantage that it is analytically simple in form. The model, given by (1), can be considered to be split into two main parts, the bracketed expression on the right being responsible for the inherent human limitations in the form of time lags in muscle actuation and information procession in the brain and nervous system. Conversely, the expression on the left is effectively a kind of counter-balance and is illustrative of the main components of the *human equalisation characteristics*.

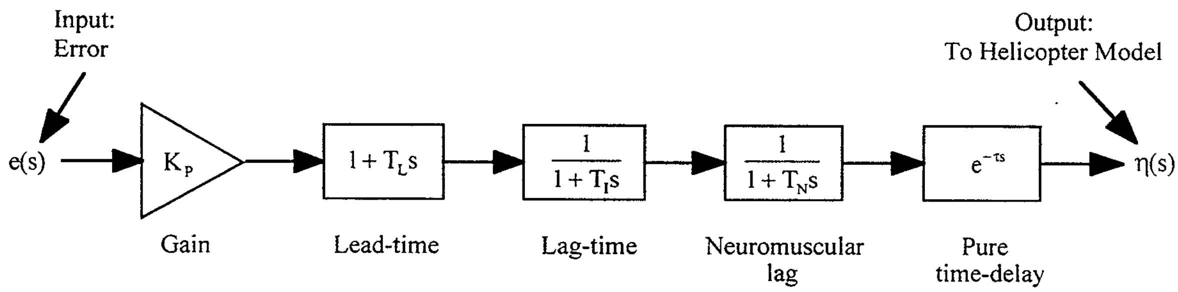

Figure 1: Block diagram of pilot model

It is considered necessary within the scope of this paper to briefly consider the variables in (1) and explain further the role assumed by each in constructing the model.

Pilot gain, K_P is a parameter which gives an indication of the pilot's ability to respond to an error in the amplitude of some controlled variable. In the case of one-axis stabilisation, the error will usually be expressed in terms of one of the Euler attitude angles of the aircraft.

Pure time-delay, sometimes known as transport-lag, $e^{-\tau s}$ is one component of the limitations inherent in all humans. It can be summarised as the difference in time between making the decision to act and the act itself occurring some fraction of a second later. Representative values of time-delay are between 0.1 and 0.25 seconds.

Lead time, T_L characterises a pilot's ability to foresee or predict a particular control action. In simple terms it can be thought of as a counter-measure to the limitations, although if used solely for this purpose, the pilot would be operating inefficiently, since utilising lead time to additionally anticipate control actions, improves performance.

The Lag time constant, T_I can be utilised to attenuate an oscillatory response, by allowing the pilot to execute smoother control inputs. This may help achieve a closed-loop compensatory task especially if the controlled element is characterised by unstable dynamics.

Neuromuscular lag, T_N constitutes the other human limitation in the model. It is concerned with the time taken to actuate the muscles after the signal from the brain has arrived to the specified limb responsible for a desired control movement.

The approach taken to construct the Precision Model was to use SIMULINK, a toolbox extension to MATLAB. This method permitted each element to be directly entered as a gain or transfer function in lead, lag etc. Figure 1 illustrates schematically how the model was implemented in SIMULINK.

Of the five variables within the Precision Model, two of them can be regarded as being essentially constant for any individual pilot, namely neuromuscular lag (T_N) and pure time-delay ($e^{-\tau s}$), the two limitations. This effectively makes the right-hand-side of (1) uninfluenced in the study. The pilot equalisation characteristics, (left-hand-side of (1)) however, are not constant and it will be shown that a proposed optimum value exists for these parameters as calculated using constrained optimisation.

The pilot model acts as the controller for a single-input-single-output (SISO) transfer function of the helicopter, which was developed via linearisation and mathematical manipulation, given below. A reference signal is applied in the form of an aircraft state parameter. For example, the reference signal in the form of a pitch attitude time-history required to fly an acceleration/deceleration as generated by Helinv is shown in Figure 2(a). The roll angle for a slalom is shown in Figure 2(b). Comparison with the signal generated by the pilot/helicopter system produces the error which is input to the pilot model and used to drive the closed-loop simulation.

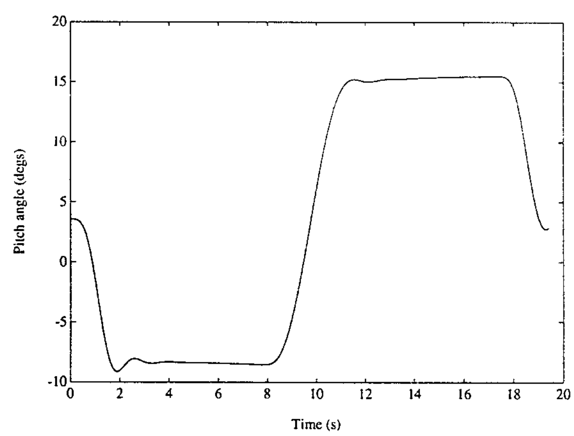

Figure 2(a): Pitch attitude for Acceleration/deceleration

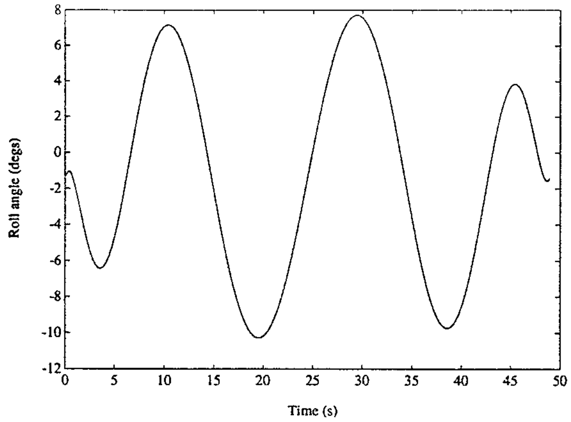

Figure 2(b): Roll attitude for Slalom

The Helicopter Model

In conventional forward simulation the exercise of calculating the response of a system to a predetermined set of control inputs is a familiar one. The initial value problem is usually expressed in the form,

$$\underline{\dot{x}} = f(\underline{x}, \underline{u}); \qquad \underline{x}(0) = \underline{x}_0 \tag{2}$$

$$\underline{y} = g(\underline{x}) \tag{3}$$

where $\underline{x}$ is the state vector of the system and $\underline{u}$ is the control vector.

For this study the helicopter model used in the state space formulation is of a rudimentary nature with only fuselage and rotorspeed degrees of freedom taken into account, and has the state vector,

$$\underline{x}=[U\ V\ W\ P\ Q\ R\ \phi\ \theta\ \psi\ \Omega\ Q_E]^T \tag{4}$$

where,

U, V, and W represent the constituent elements of translational velocity of the helicopter when expressed relative to a body fixed frame of the form (x_b, y_b, z_b).
P, Q, and R are the angular velocities about the three axes of the vehicle and,

ϕ, θ, and ψ are the Euler angles determining the attitude of the aircraft.

Ω is the angular velocity of the main rotor and Q_E is the output torque of the engines.

The corresponding control vector can be expressed as,

$$\underline{u}=[\theta_0\ \theta_{1s}\ \theta_{1c}\ \theta_{0tr}]^T \tag{5}$$

where,

θ_0, θ_{1s}, θ_{1c} represent the main rotor collective pitch, longitudinal and lateral cyclic angles respectively, while θ_{0tr} represents the tail rotor collective pitch angle.

The inverse simulation package, Helinv uses a seven degree-of-freedom model, HGS (Helicopter Generic Simulation) to obtain control responses to manoeuvre inputs. This model is also available in conventional form and hence can be used to obtain a state space representation of the vehicle dynamics about a given reference trim condition. A full treatment of HGS is given by Thomson in [5], however it is appropriate at this stage to give some brief details, for clarity. HGS is a non-linear, seven degree-of-freedom (six body and rotorspeed) model of a single main and tail rotor helicopter. Fuselage and empenage loads are estimated from look-up tables based on wind tunnel data. The main rotor is of the disc-type with quasi-steady multi-blade flapping assumed.

The state space formulation was obtained by linearising about trim conditions that captured the initial state of the helicopter. The method used involves transformation of the state equation (6) into a generic transfer function (7) relating any output variable, x to control input, u.

$$\underline{\dot{x}} = A\underline{x} + B\underline{u} \tag{6}$$

$$Y_H(s) = \frac{X(s)}{\underline{U}(s)} = (sI - A)^{-1}B \tag{7}$$

The study of the theoretical response of the aircraft can then be investigated. **Appendix A** presents the transfer function associated with the flight state for each manoeuvre, and where relevant, each aggression level. It was not necessary to derive separate transfer functions for each aggression level in some manoeuvres, for example the hover-turn, as the reference trim state (i.e. trimmed hover) remained the same for each aggression level. A transfer function was also derived to take account of the actuator dynamics, Figure 3 illustrating the implementation within SIMULINK. A first order lag was considered an adequate representation with an appropriate time constant, (τ_{cn}) being assigned to the relevant cyclic or collective channel.

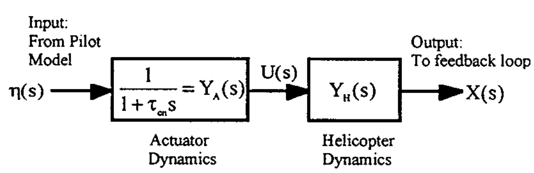

Figure 3: Model of actuator dynamics

For the Westland Lynx an appropriate transfer function in the lateral cyclic channel was found to be [11],

$$Y_A(s) = \frac{1}{1 + 0.125s} \tag{8}$$

The reference inputs to the pilot/helicopter systems are obtained by inverse simulation of appropriate Mission Task Elements. Schematics of the selected MTEs used to obtain the reference signals for system input are presented below with an example mathematical formulation of the hover-turn.

Mission Task Element Modelling

By looking at manoeuvres that used primarily, one control to execute the task, and by considering specific flight parameters that are inputs to Helinv, the following MTEs were selected;

(1). *Hover-turn,*

(2). *Bob-up/bob-down,*

(3). *Acceleration/deceleration* and

(4). *Slalom.*

An element of work previously carried out at the University of Glasgow was the development of a library of mathematical representations of ADS-33 MTEs, [12]. To maximise the scope of this study, the MTEs were selected to reflect translations in all three axes of the aircraft and at three aggression levels. Level 1 corresponds to a high aggression manoeuvre, Level 3 to a low, with Level 2 being the intermediate manoeuvre. Mathematical models of the manoeuvres are obtained by representing principal flight path parameters (component velocities or accelerations) as a series of piecewise smooth polynomial functions of time. To model the hover-turn for example, see Figure 4, the yaw-rate is defined in three sections, two cubic polynomials and a linear section,

$$\begin{aligned}
&0 < t < t_{yr} \quad \dot{\psi} = \left[-2(t/t_{yr})^3 + 3(t/t_{yr})^2\right]\dot{\psi}_{max} \\
&t_{yr} < t < t_{ho} \quad \dot{\psi} = \dot{\psi}_{max} \\
&t_{ho} < t < t_m \quad \dot{\psi} = \left[-2(t'/t_{ho})^3 + 3(t'/t_{ho})^2\right]\dot{\psi}_{max} \\
&\text{where,} \qquad t' = t + t_{con}
\end{aligned} \tag{9}$$

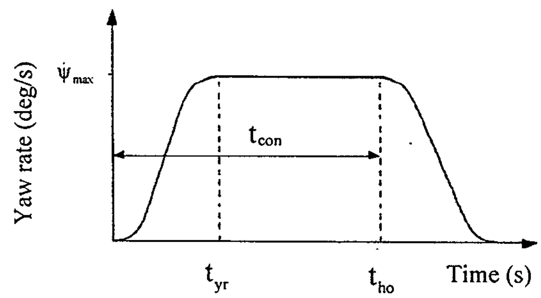

Figure 4: Yaw-rate profile for hover-turn

Parameters such as t_{yr} are inputs to the simulation and by varying the value of one (or more) of them, it is possible to vary the aggression level of the manoeuvre.

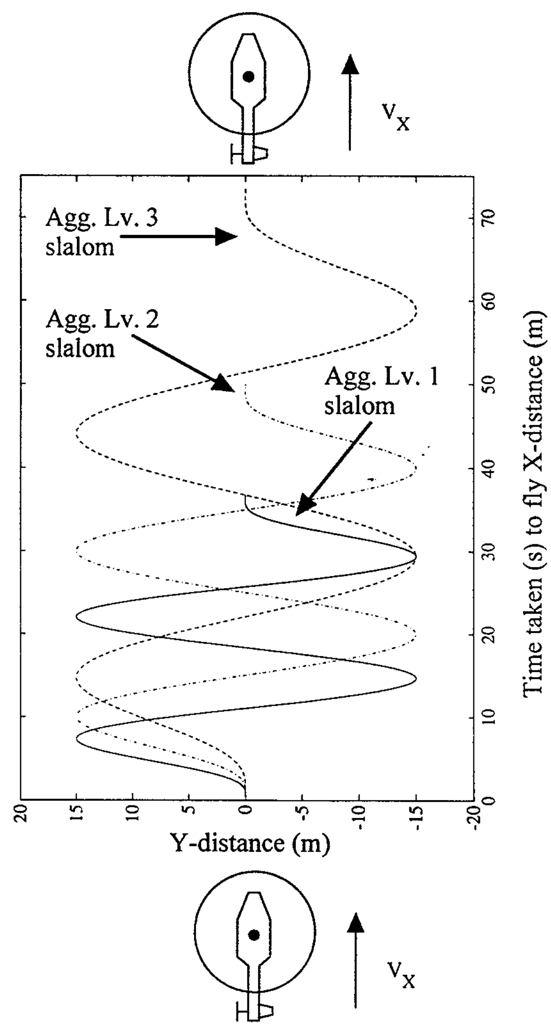

Figure 5(a): Slalom MTE

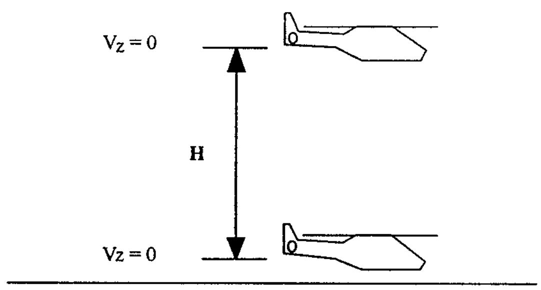

Figure 5(b): Bob-up/bob-down MTE

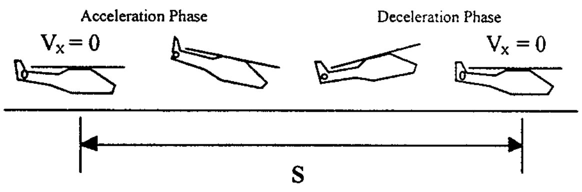

Figure 5(c): Accel./decel. MTE

Input parameters for hover-turn MTE			
Agg. Lvl.	t_m (s)	t_{yr} (s)	t_{ho} (s)
Level 1	10.0	2.0	2.0
Level 2	15.0	2.0	2.0
Level 3	20.0	2.0	2.0
Input parameters for bob-up/down MTE			
	H (m)	t_m (s)	t_{aq} (s)
Level 1	18.3	10.0	2.0
Level 2	18.3	15.0	2.0
Level 3	18.3	20.0	2.0
Input parameters for quick-hop MTE			
	t_a (s)	t_d (s)	V_X (m/s)
Level 1	1.5	3.0	42.5
Level 2	1.5	3.0	32.5
Level 3	1.5	3.0	20.0
Input parameters for slalom MTE			
	X (m)	Y (m)	Vel. (kts)
Level 1	1500	15.0	80
Level 2	1500	15.0	60
Level 3	1500	15.0	40

t_m is the total manoeuvre time
t_{yr} is the time taken to max. yaw-rate
t_{ho} time to get back to hover
t_{aq} time to acquire target in bob-up/down
t_a, t_d time to reach max. acceleration/deceleration
V_X maximum velocity

Table 1: Summary of Helinv manoeuvre parameters for each aggression level

Results from inverse simulation runs of a slalom, (Figure 5(a)), a bob-up/bob-down (Figure 5(b)) and the linear repositioning acceleration/deceleration manoeuvre (Figure 5(c)) yielded time histories of roll angle, heave velocity and pitch anngle respectively. A hover-turn MTE was also simulated, giving a yaw angle time-history. Translations in other axes were assumed negligible, which is consistent with Helinv results, which showed only small off-axis translations in all the MTEs except the slalom which clearly must yaw as well as roll to accomplish the manoeuvre.

Parameters such as the maximum velocity reached in the manoeuvre or the values of maximum acceleration and deceleration can also be varied for other MTEs. The flight parameter data input to Helinv were based on values used in recent flight simulation trials at the Defence Evaluation and Research Agency, Bedford, UK, and it is hoped that a degree of consistency will be achieved in both investigations. Table 1 summarises, for each manoeuvre, the relevant parameters supplied to Helinv, with aggression levels on the left.

The Pilot-in-the-loop System

Figure 6 illustrates the final compensatory model where $Y_P(s)$, $Y_A(s)$ and $Y_H(s)$ are the transfer functions relating to the pilot, actuators and helicopter respectively. The calculated output signal is compared with the reference input generating an error. One form of optimum settings within the pilot model may be regarded as those values which minimise the resulting error, which takes the form,

$$\text{Error (e)} = \int_0^1 (\alpha_{com} - \alpha_{new})\ dt^* \qquad (10)$$

where,

$$t^* = \frac{t}{t_m} \qquad (11)$$

and,

α_{com} is the commanded attitude angles or body velocity from HELINV, (ϕ, θ, ψ or W)

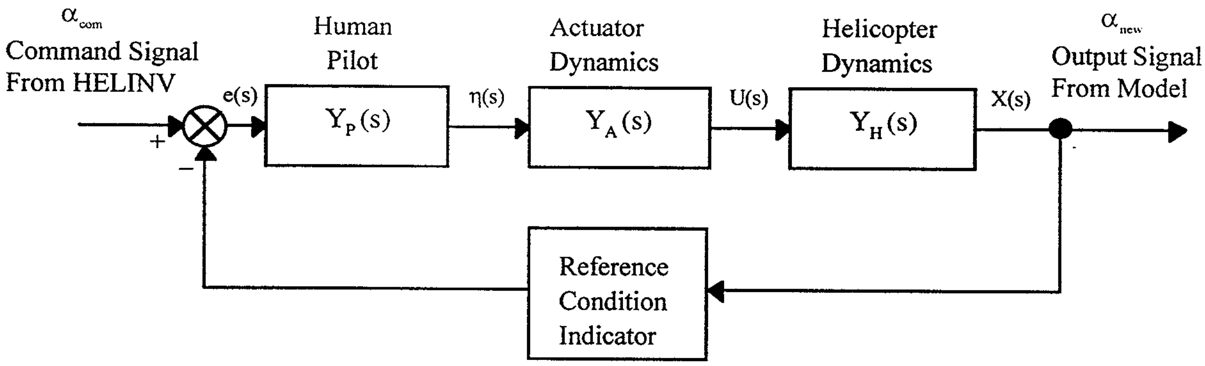

Figure 6: Single-axis tracking type system

α_{new} is the new attitude angle or body velocity from the pilot-helicopter system.

The method employed to minimise the error function was a form of constrained optimisation known as Sequential Quadratic Programming (SQP) [13]. Constrained optimisation is a technique which tries to transform the original problem into one which can be solved using an iterative solution process. The quadratic programming sub-problem is actually solved at each major iteration, so the progress of the solution technique can be viewed as the optimum point, or solution that yields the smallest error function value, is approached. The solution process itself is one that consists of two main phases, the first being the establishment of a feasible solution point, and the second involves the generation of an iterative scheme which will eventually lead to that solution point.

As the SQP method is a constrained optimisation problem, it was necessary to define boundaries for each of the three equalisation parameters. Boundary conditions for the Gain and the equalisation time constants were proposed for each variable. The upper and lower boundaries for pilot gain, K_P were set at 0.3 and 0.1 respectively for the attitude input reference signals (ϕ, θ and ψ), while for the heave velocity input signal (W) the upper and lower boundaries were selected to be 2.0 and 0.1 respectively. The upper and lower limits for the lead-time constant, T_L were set at 0.6 and 0.1 seconds respectively for all input signals. Finally, 1.2 seconds and 0.1 seconds were assumed to be appropriate limits for extremities of the lag-time constant, T_N, again, for all reference inputs.

Analysis Of Results

Before presenting analysis to the results obtained from the study, it is appropriate to detail in point form,the general procedure used for each MTE and each aggression level.

1. System and control matrices, (A and B) are calculated using HGS, for the reference trim state.

2. The flight state transfer function is calculated using the method given by (7) and the matrices obtained from HGS.

3. Mission Task Element model is obtained using Helinv with specific input flight parameters, as given in Table 1.

4. The reference input time-history is generated via inverse simulation using Helinv and the MTEs selected for 3, above.

5. Reference time-history of attitude angle or vertical body velocity input to Sequential Quadratic Programming optimisation algorithm.

6. The optimum equalisation parameters obtained in 5, are input to MATLAB/SIMULINK conventional simulation model to obtain the modified tracking time-histories from the pilot/helicopter system, presented below.

Table 2 presents a summary of the findings obtained from the simulation runs and optimisation process. The values of pilot gain, lead time constant and lag time constant read from left to right.

Figures 7(a), (b) and (c) present the results of the hover-turn MTE, with the higher aggression manoeuvre shown first. Considering Figure 7(a), the solid line represents the yaw angle time-history as generated by Helinv, whilst the broken line represents the optimum response achieved by the pilot/helicopter system. Recall that the inverse simulation result, (solid line) represents the 'perfect pilot'. The gain and equalisation time constants used to obtain the optimum response are given in the first row of Table 2.

MTE	Agg. Lvl.	K_P	T_L	T_I
Hover-turn	Level 1	0.139	0.600	0.100
	Level 2	0.127	0.600	0.100
	Level 3	0.138	0.600	0.100
Bob-up/down	Level 1	1.155	0.600	0.100
	Level 2	1.102	0.600	0.107
	Level 3	1.203	0.540	0.100
Quick-hop	Level 1	0.215	0.324	0.100
	Level 2	0.230	0.225	0.100
	Level 3	0.150	0.475	0.100
Slalom	Level 1	0.142	0.600	0.100
	Level 2	0.150	0.600	0.100
	Level 3	0.200	0.553	0.100

Table 2: Results from SQP optimisation

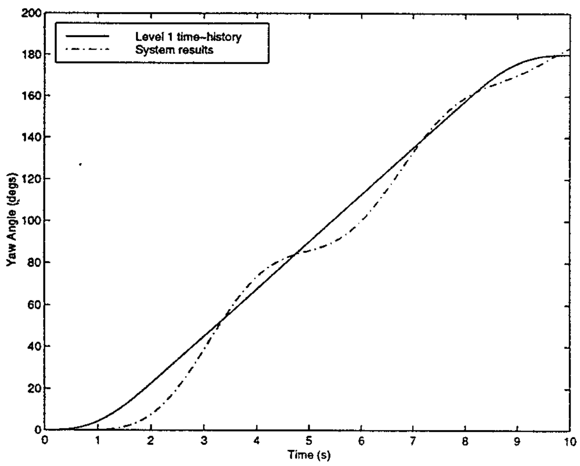

Figure 7(a): Level 1 aggression hover-turn

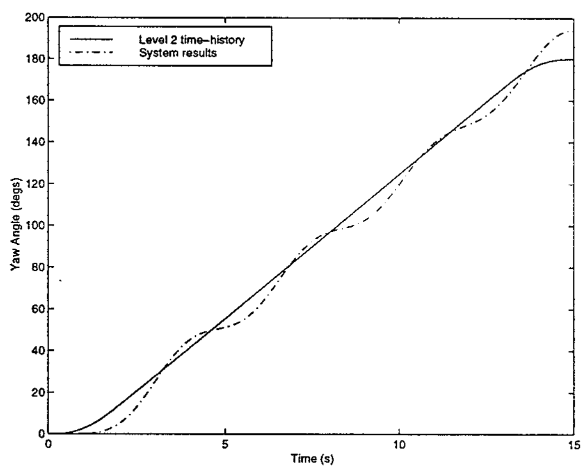

Figure 7(b): Level 2 aggression hover-turn

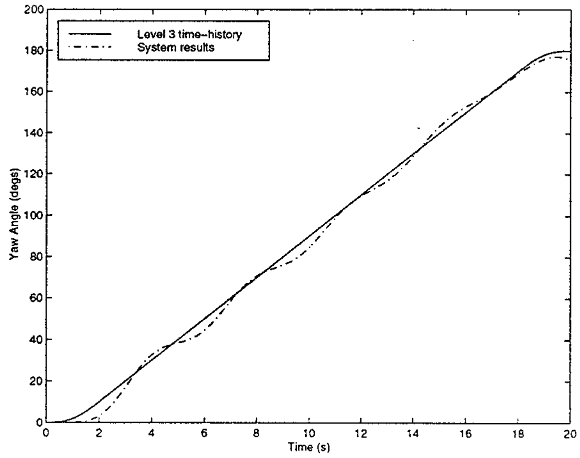

Figure 7(c): Level 3 aggression hover-turn

Figure 7(b) presents the intermediate aggression hover-turn. The broken line appears to be slightly more oscillatory but in fact provides a better tacking solution to the reference line from Helinv (solid line) than the Level 1 aggression manoeuvre. The corresponding gain, lead and lag time constants are given on row 2 of Table 2. It can be seen that the equalisation time constants have remained exactly the same, and the gain has decreased by approximately eight percent

The Level 3 aggression hover-turn results are given in Figure 7(c). It presents a similar case to Figure 7(b) but with a further decreased error margin. In keeping with the previous two aggression levels for the hover-turn, the equalisation time constants remain at 0.6 and 0.1 seconds for lead and lag respectively (row 3, Table 2). The gain has increased to a value which is extremely close to the Level 1 aggression manoeuvre. It would seem that the pilot is required to maximise the available lead time and minimise the lag time in order to accomplish this task with the lowest possible error margin. The gain is adjusted individually for each aggression level to attain the best possible performance.

The following figures present only the Level 1 aggression results for each of the remaining MTEs. However, the discussion relates to all results obtained for that particular task.

The bob-up/bob-down manoeuvre results, (Figure 8) are consistent with the hover-turn results above, in terms of maximising the lead and minimising the lag time constants. This is perhaps not surprising since both helicopter models were based on trim states in the hover and each manoeuvre initiates and terminates in the hover. The gain is of a different order of magnitude due to the difference in the state of the input reference signal. Recollect that the input reference signal for this manoeuvre is a velocity as opposed to attitude angles which is the case in reference to the other three states. The bob-up/bob-down section of Table 2 gives the final values of each parameter, (rows 4, 5 and 6).

The acceleration/deceleration analysis, shown in Figure 9, is in agreement with the hover-turn and bob-up/bob-down with reference to lag time alone, (rows 7, 8 and 9) of Table 2. The lead is not maximised, but rather follows the pattern of the gain, i.e. higher for Level 1 and 3 aggression manoeuvres and less for the Level 2.

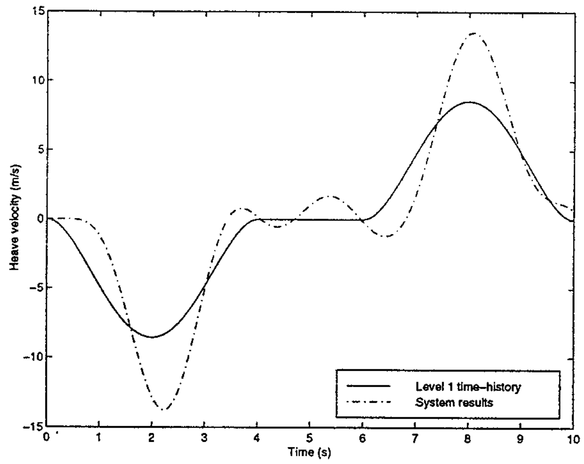

Figure 8: Helinv time-history and system results for a Level 1 aggression bob-up/bob-down

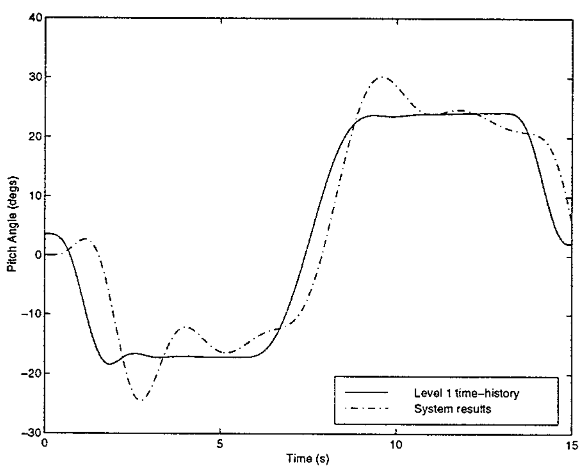

Figure 9: Helinv time-history and system results for a Level 1 aggression acceleration/deceleration (quick-hop)

Table 2 (rows 10, 11 and 12) slalom results show a continuing increase in gain as the manoeuvre aggression level is decreased, with lead time and lag time tending towards their maximum and minimum limits respectively.

Since the gain is correlated to pilot stick displacement, the slalom apparently is easier to track at higher levels of aggression. A small lag due to the human limitations is clearly visible on Figure 10, i.e. small lateral offset between Helinv perfect time-history (solid line) and the pilot/helicopter system output (broken line).

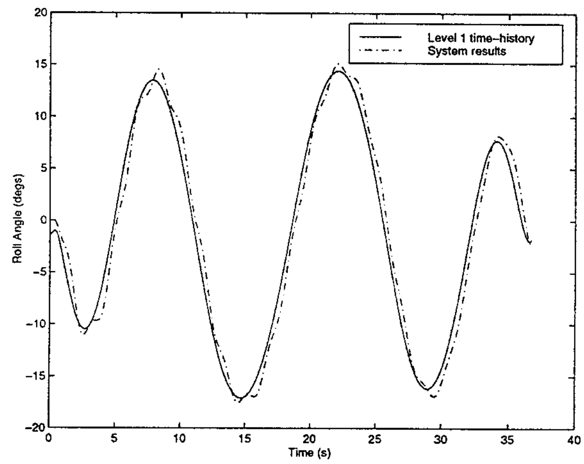

Figure 10: Helinv time-history and system results for a Level 1 aggression slalom

Conclusions

The main aim of the report was to present an new analytical method of estimating the equalisation parameters within the Precision Model. This aim has been successfully achieved and has provided insight as to the behaviour of these parameters when,

(a) time-histories from different MTEs are used as forcing functions and

(b) the aggression level of the MTE is increased or decreased. The following conclusions have been drawn from the study,

1. Pilot gain and lead time constant are variable with MTEs and differing levels of manoeuvre aggression, although for the most part the lead time constant tended toward its maximum limiting value.

2. Pilot lag time contributes to the optimum tracking condition in the MTEs and aggression levels considered when at its lowest possible value.

3. The method given in the paper does not necessarily have to be applied to one type of pilot model and may be extended to other models provided the model restrictions are adhered to.

4. It has been shown that some model 'set-ups' possess the ability to 'fly' a particular MTE more advantageously than others. This of course seems logical, the crux being however, that it has been shown using valid mathematical techniques.

Inverse simulation has been shown to be useful here as it gives, in effect, the ideal control strategy for flying a given task. This gives a datum against which other strategies may be compared, hence offering a framework for estimating pilot model parameters.

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Appendix A

MTE	Tr. Fu. $Y_H(s)$	Approximate Value of Transfer Function
Hover-turn	$\frac{\psi(s)}{\theta_{0tr}(s)}$	$\frac{-16s^{10}-356s^9-3010s^8-11835s^7-17879s^6-10475s^5-9294s^4-4114s^3-2141s^2-823s-78}{s^{11}+23s^{10}+203s^9+842s^8+1459s^7+1129s^6+859s^5+495s^4+242s^3+109s^2+27s+2}$
Slalom	$\frac{\phi(s)}{\theta_{1c}(s)}$	**Level 1 aggression** $\frac{s^{10}-153s^9-2275s^8-15144s^7-52216s^6-118736s^5-166261s^4-104193s^3-27083s^2-9639s-983}{s^{11}+25s^{10}+252s^9+1357s^8+4247s^7+8891s^6+11818s^5+6774s^4+1929s^3+636s^2+83s+3}$ **Level 2 aggression** $\frac{s^{10}-153s^9-2199s^8-13788s^7-42182s^6-82165s^5-101894s^4-59147s^3-15396s^2-559}{s^{11}+25s^{10}+239s^9+1215s^8+3400s^7+6179s^6+7417s^5+3996s^4+1108s^3+353s^2+45s}$ **Level 3 aggression** $\frac{s^{10}-153s^9-2122s^8-12447s^7-32575s^6-50314s^5-51686s^4-26684s^3-7858s^2-3072s-}{s^{11}+24s^{10}+226s^9+1067s^8+2577s^7+3780s^6+3906s^5+1911s^4+562s^3+178s^2+21s+}$
Accel./ decel.	$\frac{\theta(s)}{\theta_{1s}(s)}$	**Level 1 aggression** $\frac{s^{10}+26s^9+576s^8+4657s^7+17989s^6+30501s^5+39279s^4+22775s^3+3545s^2+168s+2}{s^{11}+24s^{10}+228s^9+1086s^8+2677s^7+4052s^6+4278s^5+2118s^4+612s^3+194s^2+23s+0.}$ **Level 2 aggression** $\frac{s^{10}+26s^9+576s^8+4494s^7+16547s^6+24031s^5+26657s^4+14077s^3+2226s^2+109s+1}{s^{11}+24s^{10}+220s^9+1011s^8+2283s^7+3000s^6+2894s^5+1371s^4+441s^3+143s^2+17s+0.3}$ **Level 3 aggression** $\frac{s^{10}+26s^9+557s^8+4307s^7+14917s^6+16981s^5+14680s^4+6665s^3+1097s^2+57s+0.2}{s^{11}+24s^{10}+212s^9+929s^8+1861s^7+1986s^6+1722s^5+834s^4+347s^3+389s^2+18s+0.8}$
Bob-up/ bob-down	$\frac{W(s)}{\theta_0(s)}$	$\frac{s^{10}+6s^9+139s^8+1057s^7+2458s^6+4118s^5+2678s^4+2107s^3+1044s^2+456s+179}{s^{11}+23s^{10}+203s^9+842s^8+1459s^7+1129s^6+859s^5+495s^4+242s^3+109s^2+27s+2}$