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The Estimation Of Precision Pilot Model Parameters Using Inverse Simulation

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Abstract

The practice of using mathematical models to simulate pilot behaviour in one-axis stabilisation tasks is a well known conventional simulation problem. In this report a system is developed whereby a mathematical model of a pilot is used as the controller of a rudimentary helicopter model. The main differences between this and other similar scenarios that have been found in the literature are that firstly, inverse simulation is used to provide results that are used as the forcing functions in the model of the pilot/helicopter system, and secondly a constrained optimisation routine is utilised to obtain values for the parameters within the pilot model itself. It will be shown that as the pilot is required to fly different manoeuvres, defined by standards set by the United States Army, or indeed if the severity of the set manoeuvres is varied, the pilot is required to adjust certain human parameters to fly the manoeuvre in a superlative manner. The report considers initially the pilot and helicopter models and subsequently analyses the system as a whole, illustrating how the pilot model can change depending on the circumstances.

1. Introduction

With the growing complexity of pilot/helicopter interface systems, the need to develop increasingly intricate mathematical models of both pilot and helicopter has become more urgent. Of equal importance though, is the ability to analyse the interaction between man and machine, and this has been the genesis of an extensive amount of research, extending into areas governing handling qualities, flight simulation and understanding of flight test data.

This report, comprised of three main sections, deals with the development and conventional simulation of rudimentary mathematical models of pilot and helicopter, in a pilot-in-the-loop situation. A more novel approach is taken from the point of view that it is inverse simulation that is used to drive the conventional simulation model and indeed, is utilised in the construction of the mathematical representation of the pilot. Section 2 considers the mathematical model of the pilot alone and how the various parameters contained within it relate to human characteristics, while the development of a simple generic transfer function relating Euler angles and pilot controls is discussed in Section 3. An analysis of the closed-loop system with pilot and helicopter model included is carried out in Section 4, where the complete system is given in closed-loop form.

Although a comprehensive treatment of inverse simulation is not required, for the sake of completeness it is necessary to describe how the inverse simulation results were employed in the pilot/helicopter mathematical modelling scenario. ADS-33D [1] describes in mathematical terms so-called Mission Task Elements (MTEs) which can be implemented as computer models and used to drive the inverse simulation. Using the inverse simulation package HELINV [2], at Glasgow University, it is possible to run simulations of the MTEs and calculate the controls required to fly the manoeuvre. Additional results from the inverse simulation include time-histories of the aircraft's attitude angles as it is flying the manoeuvre. The time-histories are stored essentially as double-column matrices of time versus attitude angle, and theoretically act as the forcing functions of the pilot/helicopter system.

The main aim of the report is to show that using results from inverse simulations, parameters within the pilot model symbolising human limitations and equalisations can be calculated using a constrained optimisation process. It is also shown that the pilot parameters vary not only with different manoeuvres but also with fluctuations in the aggression of the manoeuvre. This is achieved by choosing specific MTEs as defined by ADS-33D, and varying user inputs to alter the resulting attitude time-history. Manoeuvres in all three axes are chosen, so that corresponding transfer functions in the helicopter model can be calculated relating roll and pitch angles to lateral and longitudinal cyclic respectively, and yaw angle to tail rotor collective. The manoeuvres were also specifically chosen in different flight velocity regimes, again to investigate the effects or influences on the development of the pilot model.

The main emphasis of the report is placed upon the illustration of the fact that the pilot model parameters are affected by different manoeuvres and varying levels of aggression within the manoeuvre, suggesting that the pilot may be able to adopt an optimum strategy for particular situations, whether in potential battlefield conditions or normal civilian flight.

2. 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 [3,4]. It is however with reference to another piece of work relating to pilot-in-the-loop modelling that this section of the report is concerned [5], as it is here that the so-called analytical-verbal (precision) pilot model, developed in the mid 1960s is introduced.

2.1 Precision Model

The precision model is perhaps more widely known as the crossover model, although strictly speaking, this is erroneous as the latter is an approximation of the former, which, when given as a transfer function assumes the form,

$$Y_P(s) = K_P \cdot \frac{(1 + T_L \cdot s)}{(1 + T_I \cdot s)} \cdot \left\{ \frac{e^{-\tau \cdot s}}{1 + T_N \cdot s} \right\} \tag{2.1}$$

A mathematical model of this nature obviously does not take into account all of the variables concerned with a helicopter pilot but it does encompass a reasonable amount of data when applied to specific tasks and has the advantage that it is simple in form.

The model can be considered to be split into two main parts, the bracketed expression on the right being responsible for the inherent limitations that humans possess, in the form of neuromuscular lags or delay times in the signal from the brain reaching the limb responsible for control movement in the aircraft. Conversely, the expression on the left is a kind of counter-balance and is illustrative of the so-called human equalisation characteristics.

It is considered necessary within the scope of this paper to individually consider the five variables in equation (2.1) and explain further the role they play in constructing the mathematical model of the pilot.

1. Pilot gain, $\mathbf{K_P}$ is perhaps the most difficult to visualise physically in a pilot. It is a parameter which characterises the pilot's ability to react to an error in the magnitude of a controlled variable within the flight regime. In a helicopter pilot this could take the form of having to apply more longitudinal stick force in order to maintain a desired pitch attitude.

2. Pure time-delay or transport-lag, $e^{-\tau \cdot s}$ is the first component of the inherent limitations which are present in all humans, and in a pilot represents the summation of delays between receiving information from the eyes, transmission of that information to the brain, making a decision based on the information to execute a control movement and the actual control movement occurring; representative values of time-delay are between 0.1 and 0.25 seconds.

3. Lead time, T_L is one of the human equalisation characteristics and is indicative of a pilots ability to foresee or predict a particular control action in the aircraft. Effectively it can be thought of as a counter-measure to time-delay and neuromuscular lag, although if it were used solely for this purpose, the pilot would not be operating as efficiently as one who utilises lead time to anticipate control actions.

4. In the same way that a pilot can use lead time to predict errors that might occur, hence giving him the ability to potentially rectify the situation, it is also possible to use Lag time, T_I for similar purposes, a typical example being the application of smoother control inputs in order to attenuate an unpleasant flight condition.

5. Neuromuscular lag, T_N comprises the second human limitation and is very similar to pure time delay. It is concerned with the actuation of the muscles after the signal from the brain arrives to the specified limb. A typical value for neuromuscular lag is approximately 0.1 seconds. There are various ways in which the neuromuscular lag can be taken into account within equation (2.1) which include a second order form [3], however it was assumed that the first order linear approximation given above would be adequate for the task in hand.

2.2 Model Restrictions And Assumptions

Briefly mentioned above was the fact that the model is a good approximation of a human pilot and encapsulates most of the data involved in pilot modelling. This is true however, only if the model is implemented under conditions that restrict it to performing particular tasks, a specific example of which is the control of one individual variable within the whole environment of helicopter flight. This could take the form of stabilisation of the longitudinal modes of the aircraft, where essentially, the pilot is given some indication of the pitch attitude of the aircraft (artificial horizon indicator), and is required to input control movements to minimise the error between some desired reference condition and the actual pitch attitude of the aircraft. Since the report is dealing with single axis control, and the MTEs have largely been chosen to reflect this, it is a reasonable to assume that an adequate representation of real life helicopter flight has been attained due to the fact that the manoeuvres last for a comparatively short period of time and other piloting tasks can be neglected over that duration.

Several basic assumptions have been identified [6], concerning the application of the model, two of the most mportant being

- the helicopter model that is to be controlled by the operator is assumed to be linear
- complete undivided attention by the operator is assumed while executing the single-axis stabilisation task

The third assumption is merely stating the fact that the ‘pilot’ is presented only with an error signal derived from the comparison between the reference or required attitude and the attitude of the helicopter at that point in time, and it will be shown in Section 2.3, when the model is implemented that this is the case.

2.3 Pilot Model Implementation

The approach taken to model the system was to utilise the dynamic system simulation software package ‘SIMULINK’ [7], which is an extension to ‘MATLAB’ [8]. This enabled the construction of the system in block diagram format, where each block was representative of individual elements in the pilot model, i.e. transfer functions of lead, lag etc. could be entered directly into the model.

Figure 2.1 illustrates in block diagram format the how the pilot model was implemented within the overall pilot-helicopter system. Basically, a reference signal is received in the form of an Euler angle time-history of the manoeuvre, (see Figures 2.2a - d), which was obtained from HELINV. Comparison of this commanded reference signal with that generated by the model simulation produces an error (e), which in turn is fed into the pilot model and is used to drive the simulation in a closed-loop scenario.

3. The Helicopter Model

The approach taken in this section of the work was to develop a single-input-single-output (SISO) transfer function that would adequately model a helicopter in a single-axis situation. In order to do this it was required that the helicopter system dynamics be linearised about some trim condition to obtain the state-space matrices. The following sections describe how this process was carried out using standards as specified by the Aeronautical Design Standard (ADS-33D) document, and Helicopter Generic Simulation (HGS) software developed at the University of Glasgow .

3.1 Helicopter Generic Simulation (HGS)

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

$$\dot{\underline{x}} = f(\underline{x}, \underline{u}); \qquad \underline{x}(0) = \underline{x}_0 \tag{3.1}$$

$$\underline{y} = g(\underline{x}) \tag{3.2}$$

where $\underline{x}$ is the state vector of the system and $\underline{u}$ is the control vector. The helicopter mathematical model used to obtain the state space matrices was of a rudimentary nature with only fuselage and rotor degrees of freedom taken into account. The resulting eleven degree of freedom state vector has the form,

$$\underline{x}=[u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi\ \Omega\ Q_E]^T \tag{3.3}$$

where,

u, v, 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, r	are the angular velocities about the three axes of the vehicle,
ϕ, θ, ψ	are the Euler angles determining the attitude of the aircraft which relate the body fixed axes set to the earth fixed inertial frame, which has the form (x_e, y_e, z_e),
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,

$$\underline{u}=[\theta_0\ \theta_{1s}\ \theta_{1c}\ \theta_{0tr}]^T \tag{3.4}$$

where,

θ_0, θ_{1s}, θ_{1c} represent the main rotor blade pitch angles and θ_{0tr} represents the tail rotor collective pitch angle.

3.1.1 Main Elements Of The HGS Model

It is considered unnecessary within the scope of this paper to fully elaborate on the HGS mathematical model, as a full treatment of the subject can be found in [9], however, this section is intended to give a brief outline of the main details of the model and how it was constructed. There are four main constituent elements that are modelled in HGS; the main rotor, tail rotor, fuselage and empenage, and in keeping with the development of most other models of dynamic systems the initial starting point is to develop equations describing the motion of the system.

The HGS main rotor and tail rotor models are paramount to the entire system, due to the fact that the fuselage and empenage can be accounted for by the use of so-called look-up tables, which are basically simple functions of the angle of attack or sideslip. The fact that the flow of air around the fuselage and empenage of a helicopter is extremely convoluted dictates that the model be either very complex or relatively simple. The look-up tables have been obtained from wind-tunnel test data and the aerodynamic coefficients of forces and moments can be found for the fuselage, fin and tailplane.

The main and tail rotor models are based on the blade element method, which is an extension to simple aerofoil theory, with the exception that it is applied to calculate the same parameters on a rotating blade. The main difference between the main and tail rotor models is that the latter assumes rigid blades and therefore does not take blade flapping into consideration. Essentially, the velocity of an individual blade element is a function of its radial position along the rotor blade and the azimuth position on the rotor disc. From the effective incidence which has been calculated, the aerodynamic forces can be obtained at any point on the disc, and in a similar manner the inertial loads are calculated from the accelerations which are also known at any position on the rotor disc.

3.2 State-space To Transfer Function Calculations

The software package Helicopter Generic Simulation (HGS) based on the mathematical description given in the previous section, at the University of Glasgow is capable of delivering the state space matrices of a multitude of given trimmed flight conditions. Essentially this is accomplished by linearising the system in trimmed flight and computing the partial derivatives with respect to all of the available state and control variables mentioned in section 3.1. Having obtained the required sets of matrices the state equation of the system can be written as,

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} \tag{3.5}$$

and taking the Laplace transform of (3.5) yields,

$$s\underline{X}(s) = A\ \underline{X}(s) + B\ \underline{U}(s) \tag{3.6}$$

which can be rearranged into the form,

$$(sI - A)\ \underline{X}(s) = B\ \underline{U}(s) \tag{3.7}$$

giving the resultant equation,

$$\frac{\underline{X}(s)}{\underline{U}(s)} = (sI - A)^{-1}\ B \tag{3.8}$$

This generic formula may then be used to obtain the transfer function relating any of the Euler angles to the control which most influences them, for example roll angle (ϕ) to lateral cyclic (θ_{1c}). The trim conditions chosen for the simulations were based on individual MTEs defined by ADS-33D, descriptions of which, and reasons for choice are given in section 3.3.

3.3 Mission Task Element Selection

An element of work previously carried out at Glasgow University was the development of a library of basic manoeuvres which were designed to encompass the rigorous demands of ADS-33 [10]. In order to obtain as wide a variety of results as possible, it was decided to carry out a classic straightforward manoeuvre in each of three axes, specifically the MTEs; Hover-turn, and the so-called linear repositioning manoeuvres, Side-step and Quick-hop, Figures 3.1a - c. A Slalom MTE was also conducted, Figure 3.1d, as this required even greater utilisation of the controls to adhere to the manoeuvre specifications, although it is the roll-axis that is of primary importance. In addition to the fact that time-histories for roll, pitch and yaw can be obtained from these manoeuvres, via inverse simulation, they are all performed in different sections of the flight envelope. The hover is defined as a precision task, the side-step is performed in the low speed range, (up to approximately 45 kts), and the quick-hop and slalom are defined as a manoeuvres which should take place in the forward flight domain, (up to never exceed velocity, V_{ne}).

3.3.1 Mission Task Element Variation

Subsequent to defining the actual MTEs, it was necessary to define different levels of aggression in the each manoeuvre, in order to generate a series of differing time-histories. The user inputs to the inverse simulation program, HELINV allow control of the aggression or severity of a particular MTE by specifying the time taken to reach maximum acceleration or deceleration, in addition to the maximum velocity reached in the manoeuvre; the maximum value of acceleration and deceleration can also be varied. Table 1 is a summary of the parameters supplied to the program to obtain the various time-histories for each manoeuvre.

Manoeuvre	HQR Level	Manoeuvre Parameters			
		t_a (s)	t_d (s)	Velocity (kts)	Acceleration (m/s/s)
Side-step	1	1.25	1.25	40	5.0
	2	1.75	3.50	25	4.0
	3	5.00	10.00	10	1.0
		t_a (s)	t_d (s)	Velocity (kts)	Acceleration (m/s/s)
****Quick-hop**	1	1.50	3.00	60	5.0
	2	4.00	8.00	25	3.0
	3	5.00	10.00	15	1.0
		t_y (s)	t_h (s)	Velocity (kts)	
Hover-turn	1	1.50	1.50	5	
	2	3.00	3.00	10	
	3	5.00	5.00	15	
				Velocity (kts)	
Slalom	1			52	
	2			35	
	3			20	

Table 1. MTE parameters used to obtain time-histories of Euler angles

where,

t_a (s) is the time to reach maximum acceleration in the linear repositioning manoeuvres

t_d (s) is the time to reach maximum deceleration in the linear repositioning manoeuvres

t_y (s) is the time taken to reach maximum yaw rate in the hover-turn MTE

t_h (s) is the time taken to return to the hover condition in the hover-turn MTE

HQR is the so-called Handling Qualities Rating, elaborated in Section 3.3.2

Figures 3.2 a -c, illustrates the acceleration profiles of the linear repositioning manoeuvres and the hover-turn to further explain the meaning of the above parameters.

3.3.2 Handling Qualities Rating (HQR)

Figure 3.3 illustrates the Cooper-Harper handling qualities rating decision tree. Test-pilots have to be extremely familiar with this scale and how to use it correctly, as well as be aware of potential pitfalls that it may present. Handling qualities ratings are judged by the pilot whose decision emanates from taking into account the flying qualities characteristics of the helicopter and the environmental task cues. Potentially, an aircraft that has a Level 1 HQR rating in perfect flying conditions during the day may degrade to Level 2 or 3 at night while performing the same manoeuvre; similarly poor weather conditions may adversely affect the rating. The ratings can be obtained numerically, and a more comprehensive treatment of the subject can be found in [11] and [12], however, in some cases sufficient information does not exist in order to quantify HQR ratings for particular manoeuvres. The Quick-hop (double asterisk in Table 1) is one particular longitudinal manoeuvre that remains to have the lower Level 3 boundary defined in ADS-33D. In order to preserve continuity throughout the experiment it was decided to introduce a manoeuvre of poor handling qualities that fell below the Level 2 rating, and it was assumed that this would be adequate for defining a Level 3 manoeuvre.

3.4 Helicopter Model And Actuator Dynamics Model Implementation

The mathematical models of the actuator dynamics and the helicopter were constructed within the 'SIMULINK' environment in exactly the same manner as the mathematical model of the pilot. Figure 3.4 illustrates in block diagram format how the actuator dynamics and the helicopter were taken into consideration. A first order lag is considered an adequate representation of the actuators with an appropriate time constant, (τ_{cn}) being assigned to the relevant cyclic channel. In a physical sense a control movement by the pilot generates a signal which is delayed by a specific amount of time by the actuators, before proceeding to the swashplate, which controls the movement of the rotor blades. The resulting signal in the form of an attitude angle from the helicopter model is a consequence of the movement and thrust magnitude of the rotor disc. This signal is fed back to the summing junction in the loop where it is compared with the reference or commanded signal from the HELINV input time-history. An error is generated which is in turn fed into the pilot model, and the whole closed-loop process is again initiated. This cycle is repeated until the attitude time-history forcing function terminates.

4. Analysis Of The Pilot-in-the-loop System

Section 2.1 described the precision model and it's constituent elements. It was decided that of the five variables, two of them are essentially constant for any one individual, namely neuromuscular lag and pure time-delay, the two inherent limitations. The pilot gain, lead and lag times however, are not constant and in fact it will be shown that the optimum values of these parameters change as the manoeuvre severity is increased or decreased or indeed if the manoeuvre itself is changed, from say a precision task like the hover-turn MTE to a linear repositioning MTE such as the side-step or the quick-hop.

4.1 Generation Of The Error Function

Figure 4.1 illustrates in simplified form the final model effected in 'SIMULINK', where $Y_P(s)$, $Y_A(s)$ and $Y_H(s)$ are the transfer functions relating to the pilot, actuators and helicopter respectively, while Figure 4.2 presents this with specific reference to pitch axis stabilisation. It has been stated that the signal is fed back and compared with the reference input which in turn generates a numerical error. It is fair to say that the optimum settings within the pilot model may be regarded as those values which minimise the resulting error, which has the form of an integral of the error squared type function,

$$\text{Error (e)} = \int_0^1 (\alpha_{com} - \alpha_{new}) \; dt^* \qquad (4.1)$$

where,

$$t^* = \frac{t}{t_m} \qquad (4.2)$$

and,

t_m is the time taken to complete the total manoeuvre, see Figures 3.2a - c

α_{com} is the commanded attitude angle from HELINV, (ϕ, θ and ψ)

α_{new} is the new attitude angle from the pilot-helicopter system

4.2 Minimisation Of The Error Function

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 an easier one which can then 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.

4.2.1 Boundary Selection For Constrained Optimisation

As the SQP method is a constrained optimisation problem, it was necessary to define boundaries for each of the three pilot model parameters; gain, lead and lag. On reviewing the literature [3] [5], appropriate limits or boundary conditions were set for each variable. The upper and lower boundaries for pilot gain were set at 0.3 and 0.1 respectively, while the same respective limits for lead-time were set at 0.6 and 0.1 seconds. Finally, 1.2 seconds and 0.1 seconds were assumed to be appropriate boundary limits for the upper and lower extremities of pilot lag-time.

4.2.2 Problems Associated With Boundary Limit Choice

It was found that if the above boundary conditions were imposed, the optimisation process would terminate prematurely at a local minimum. Obviously this was an undesirable situation, and to alleviate the problem the boundaries for each parameter were sub-divided into groups of four, sub-boundaries in the following manner,

Pilot gain, K_P	[0.10 - 0.15], [0.15 - 0.20], [0.20 - 0.25] and [0.25 - 0.30],
Lead-time, T_L	[0.10 - 0.225], [0.225 - 0.35], [0.35 - 0.475] and [0.475 - 0.60]
Lag-time, T_I	[0.10 - 0.375], [0.375 - 0.65], [0.65 - 0.925] and [0.925 - 1.2]

The optimisation process was automated in a fashion that allowed all possible permutations of the groups of boundaries, thus finding the minimum which is most likely to be a global one. In this way the lowest possible solution of the error function could be found using any combination of pilot model parameters, hence providing optimum values for the lead, lag and gain for any single particular manoeuvre, or level of aggression within that manoeuvre.

4.3 Results Of Simulation Runs

Table 2 summarises the results obtained from the simulation runs, and presents the final values of the minimised error function and the optimum values for the pilot model for that particular MTE or HQR level within the MTE.

Manoeuvre	HQR Level	Error (e)	Pilot Gain (K_P)	Lead Time (T_L)	Lag Time (T_I)
Side-step	1	129.42	0.100	0.600	0.100
	2	27.73	0.144	0.600	0.100
	3	0.34	0.279	0.179	0.100
Quick-hop	1	116.52	0.157	0.600	0.100
	2	4.17	0.200	0.600	0.100
	3	0.42	0.281	0.321	0.100
Hover-turn	1	292.07	0.177	0.600	0.100
	2	23.73	0.171	0.600	0.100
	3	5.94	0.188	0.538	0.100
Slalom	1	132.57	0.207	0.369	0.100
	2	15.25	0.231	0.284	0.100
	3	1.85	0.248	0.217	0.100

Table 2. Final results of minimum error values and optimum pilot model parameters

It can be seen from the table that as the HQR level of the manoeuvre is decreased the error between the input forcing function or time-history of the MTE, and the resulting time-history from the system is reduced. It is probable that this occurs primarily due to the fact that the HQR level 3 manoeuvres are of a much lower frequency, that is, the control actions of the pilot occur at greater intervals than the level 1 manoeuvres, and because the level 3 manoeuvres can take up to three times longer to complete, the system has more time to compensate and adapt itself to the input signal. Perhaps the MTE that most confirms the importance of the length of time taken to complete the manoeuvre is the hover-turn, Figures 4.5a - c. The main reason for this is the fact that the terminating angle of Yaw in the manoeuvre is always the same, i.e. 180 degrees, therefore it must be the time that has most influence over the degree of accuracy to which the system can track the input time-history.

Figures 4.3a - c serve to further illustrate this point as the time-histories obtained from a HELINV side-step MTE are plotted with the results from the pilot/helicopter system. The level 3 results seem to have less phase lag and are more accurate in the values of amplitude that are shown. Similar results are to be found in Figures 4.4a - c and 4.6a - c for the quick-hop, and slalom Mission Task Elements respectively.

5. Conclusions

The main aim of the report as stated at the outset was to establish the fact that the parameters within the pilot model can and do change as; (a) the manoeuvre or MTE is changed and (b), the severity of the MTE is altered from an aggressive attacking strategy to a more gentle, benign approach. It is possible to draw conclusions in a dual sense, firstly on a general level referring to both pilot and helicopter and secondly, from a more specific point of view dealing only with the three main parameters within the pilot model.

- The main aim of the report has been satisfied as it has been shown that pilot gain, lead time and lag time do vary as the manoeuvre is changed from say a precision task to an attacking, aggressive MTE
- With the above point in mind, it is feasible to assume that the pilot model is manoeuvre specific, and any observable trends in the pilot model for one specific MTE do not necessarily apply to another
- An additional implication is the fact of pilot individuality, that is, some pilots may possess the ability to fly a particular MTE more advantageously than others. This of course seems logical, the crux being however, that this has been shown mathematically

The Linear Quadratic Programming (LQP) algorithm performed the optimisation process on the three main pilot model variables and obtained results as given in Table 2. It is possible to substantiate the results and draw the following conclusions with reference to each of the individual pilot model parameters

- Pilot gain: It can be seen that as the HQR of each manoeuvre degrades from 1 to 3 the general trend of the pilot gain is to increase. Initially it was thought that the opposite should be the case, however, it is likely that the main influence here is the velocity at which the helicopter is travelling. The faster speeds are associated with higher HQR ratings and it is likely that less effort in terms of stick force is required to perform the manoeuvre. The exception to the general trend in pilot gain is the hover-turn MTE, which actually fits the hypothesis in that no translational velocity is present during the execution of this manoeuvre.

- Lead time: It is probable a pilot would operate more efficiently during an aggressive manoeuvre with increased forethought or preconception of what is likely to happen. Effectively then, an increase in lead time is likely to be required during a manoeuvre which takes place over a short period of time, as opposed to one which is more gentle and occurs over the period of say 30 seconds. This trend is observable in the results, in three of the MTEs, the exception to the rule again being the hover-turn, where the optimum situation is to have 0.6 seconds of lead time for all three HQR level manoeuvres.

- Lag time: A very simple conclusion can be drawn with reference to lag time, basically it is desirable to have a very small lag time to reach an optimum state. All manoeuvres returned a value of 0.1 seconds which is very small and perhaps unachievable in realistic sense, however it does serve a purpose in the one-axis stabilisation scenario presented in the report. It was previously stated that lag time is best utilised in attenuation type duties, like improving the so-called 'ride-quality' of a manoeuvre instead of actually improving the efficiency of which the pilot can complete the MTE.

It remains only to be said that there is potentially a great deal of work that can be carried out in this regime, in quantifying pilot workload and relating this to corresponding HQR levels and parameters within the pilot model. Utilising other more complex forms of pilot and helicopter models is perhaps another method by which the current work can be justified fully.

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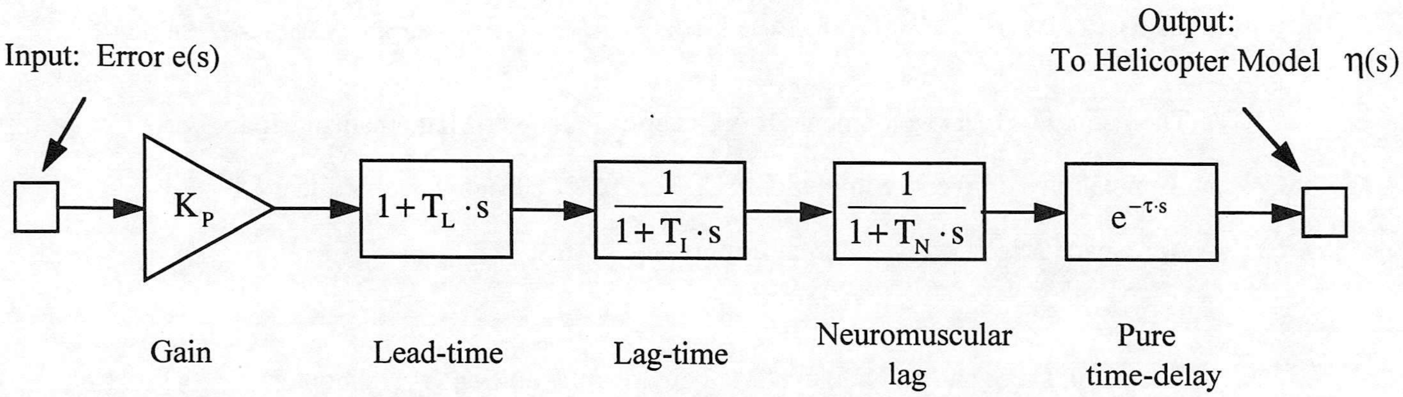


$$Y_P(s) = \frac{\eta(s)}{e(s)} = K_P \cdot \frac{1+T_L \cdot s}{1+T_I \cdot s} \cdot \frac{e^{-\tau \cdot s}}{1+T_N \cdot s}$$

Figure 2.1: Block diagram of pilot model

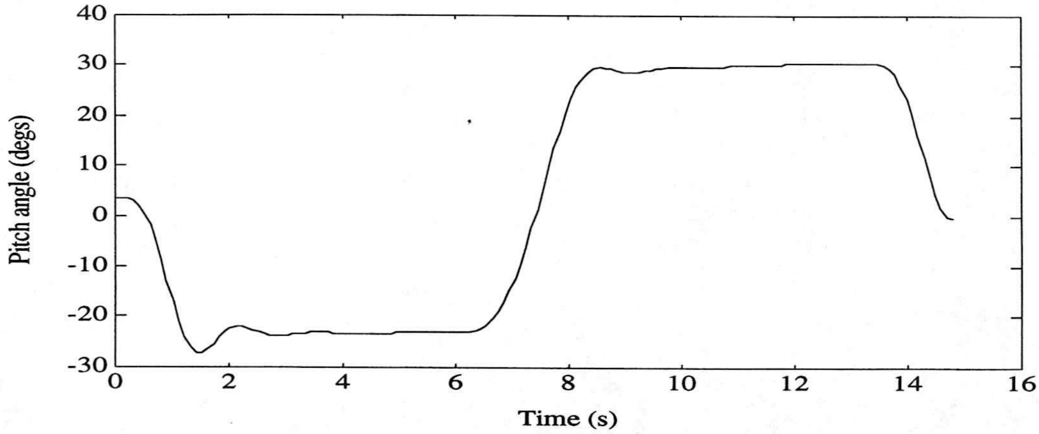


Figure 2.2a: Example time-history from quick-hop MTE

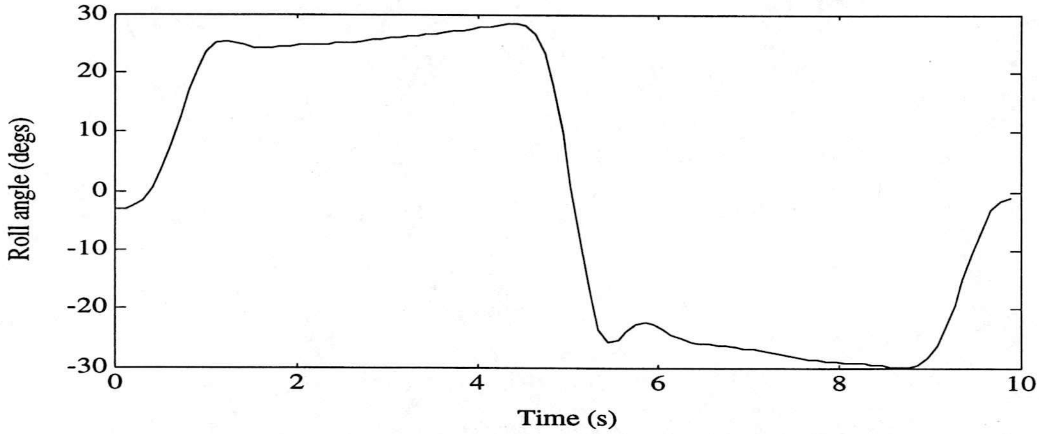


Figure 2.2b: Example time-history from side-step MTE

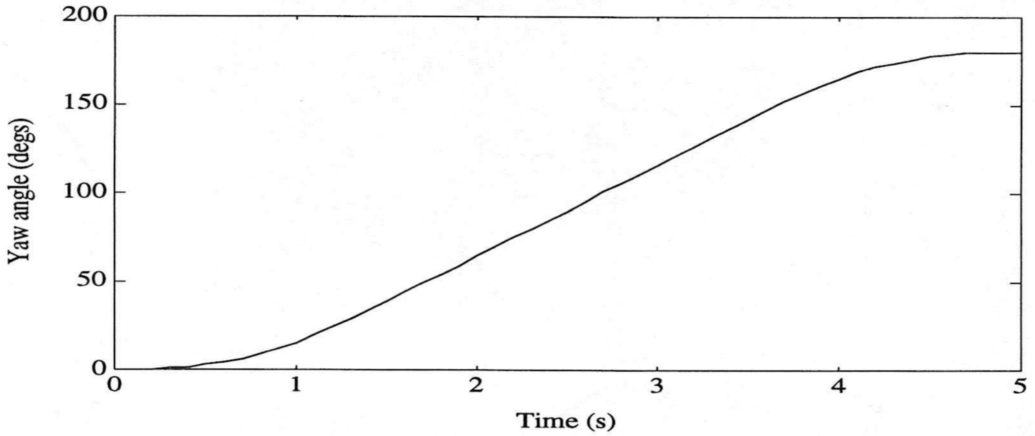


Figure 2.2c: Example time-history from hover-turn MTE

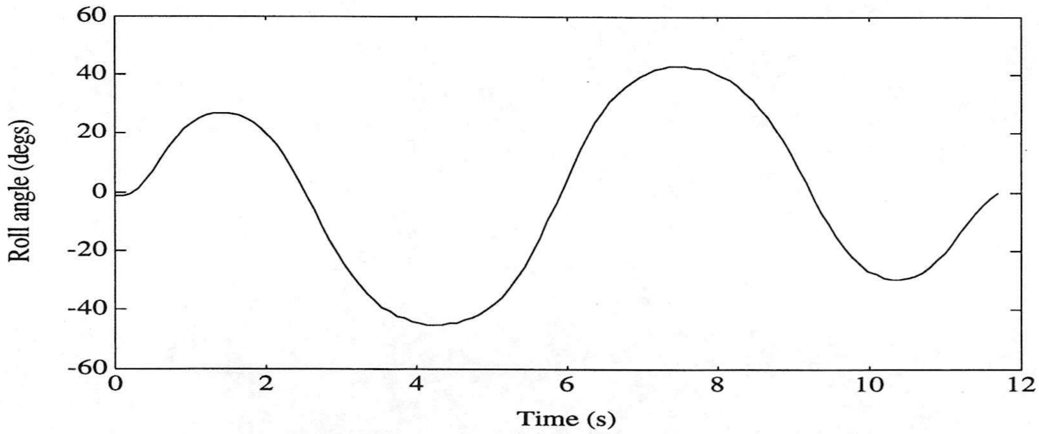


Figure 2.2d: Example time-history from slalom MTE

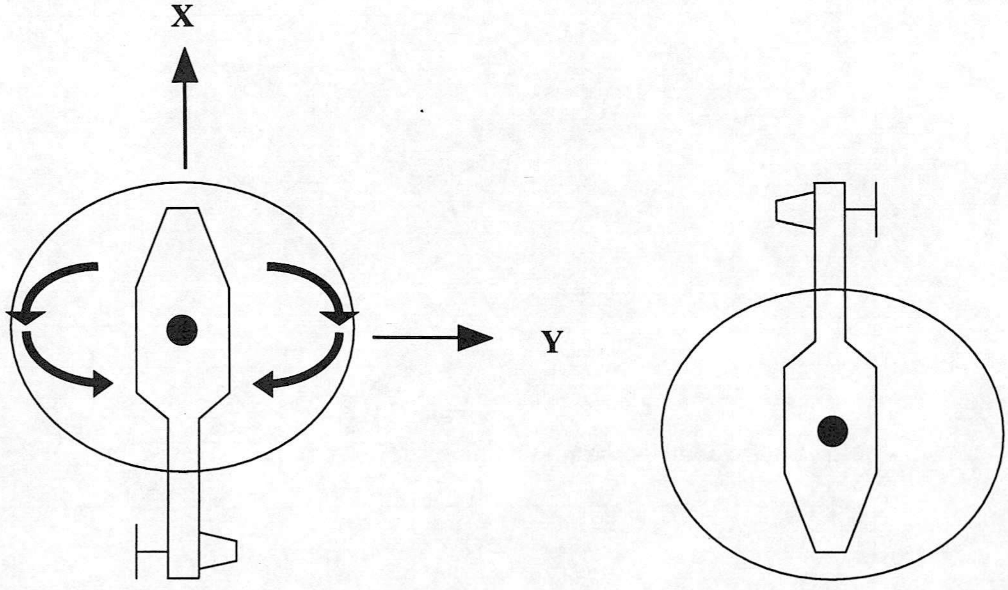


Figure 3.1a: Hover-turn Mission Task Element

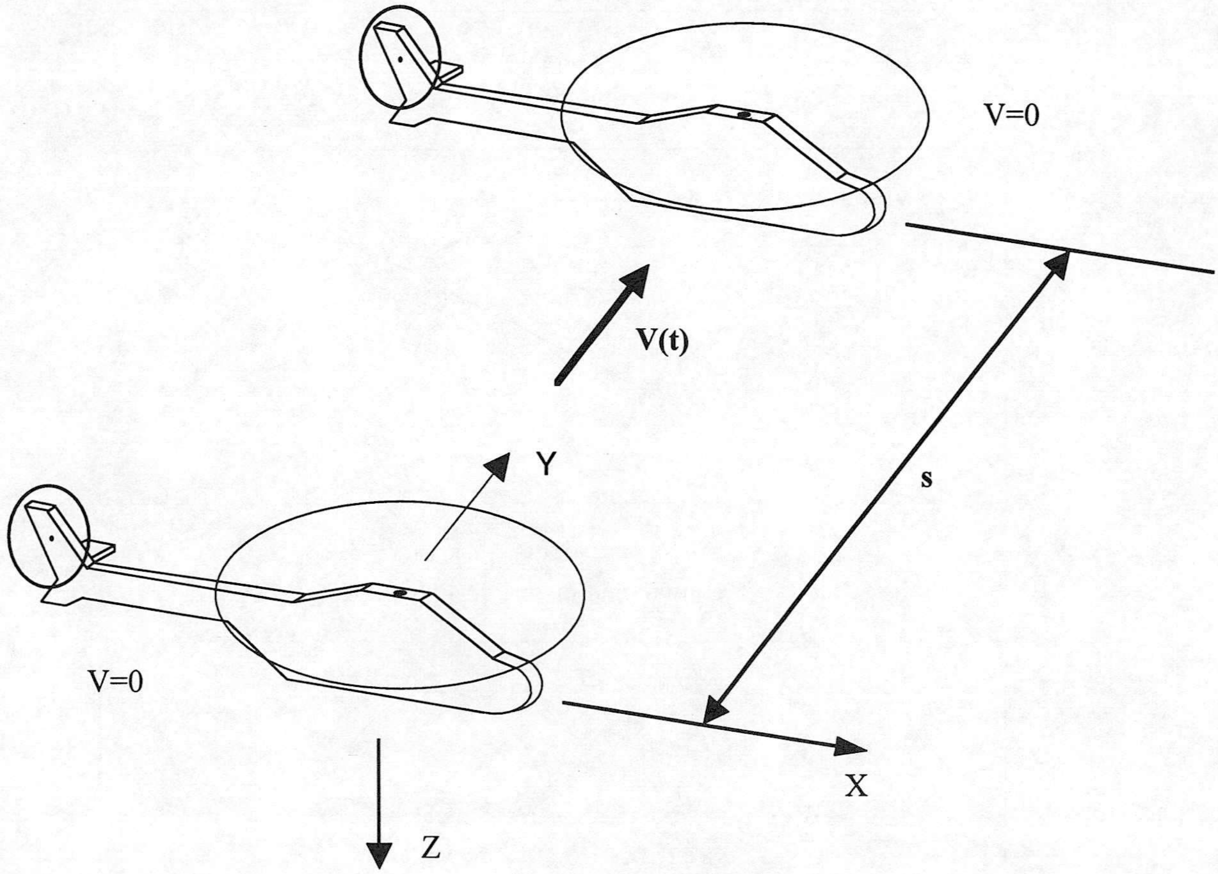


Figure 3.1b: Rapid side-step Mission Task Element

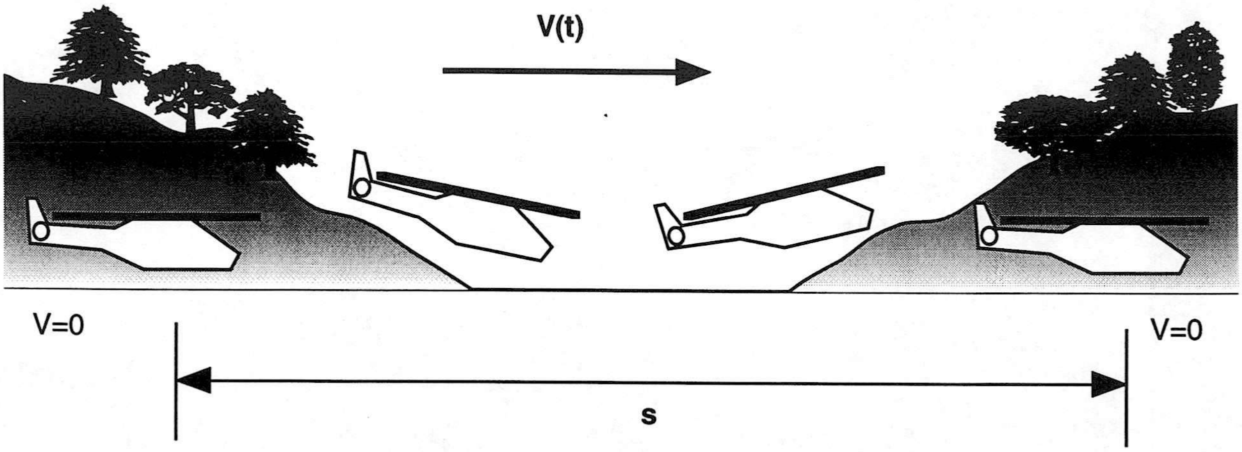


Figure 3.1c: Quick-hop Mission Task Element

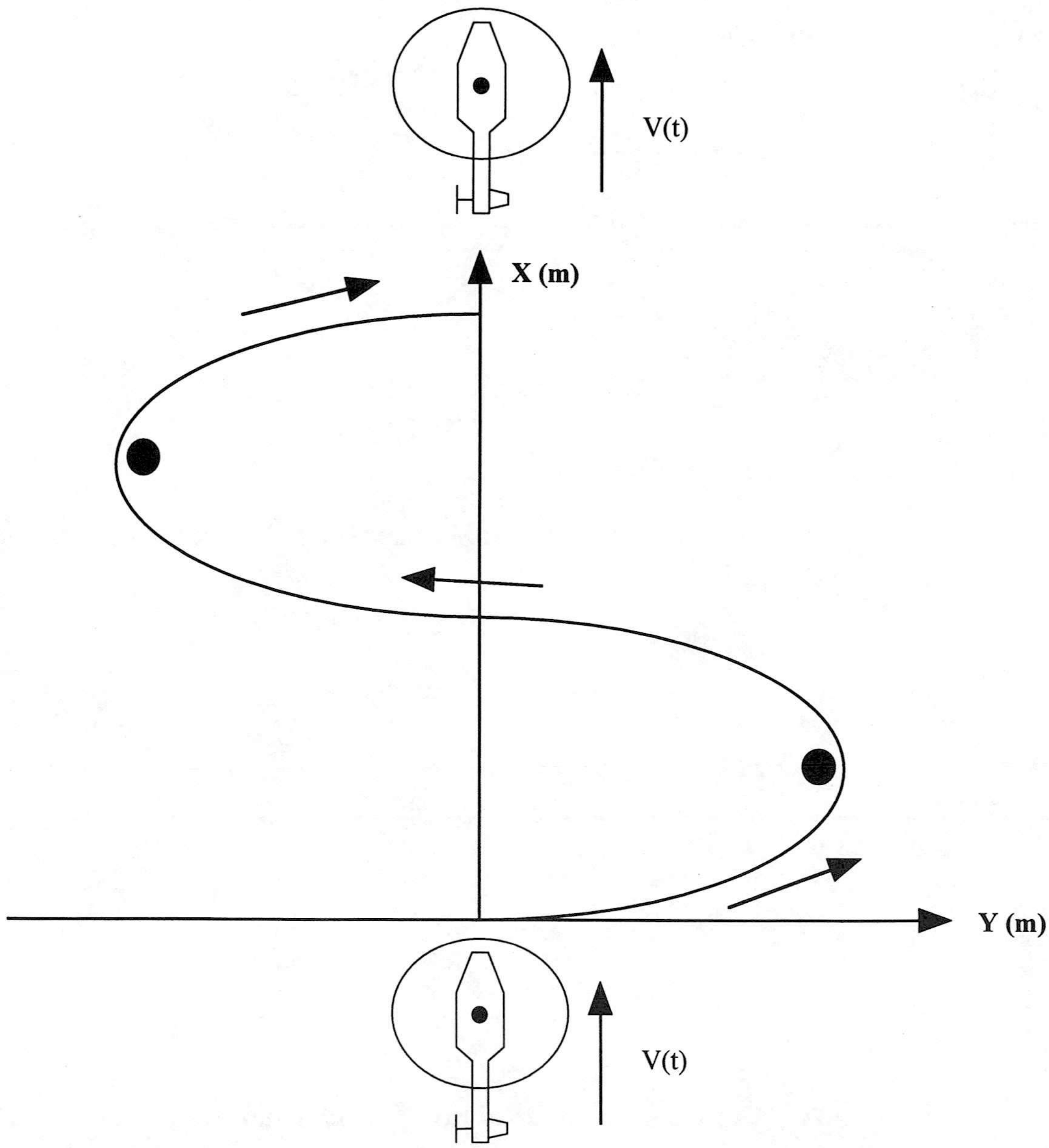


Figure 3.1d: Track of Slalom Mission Task Element

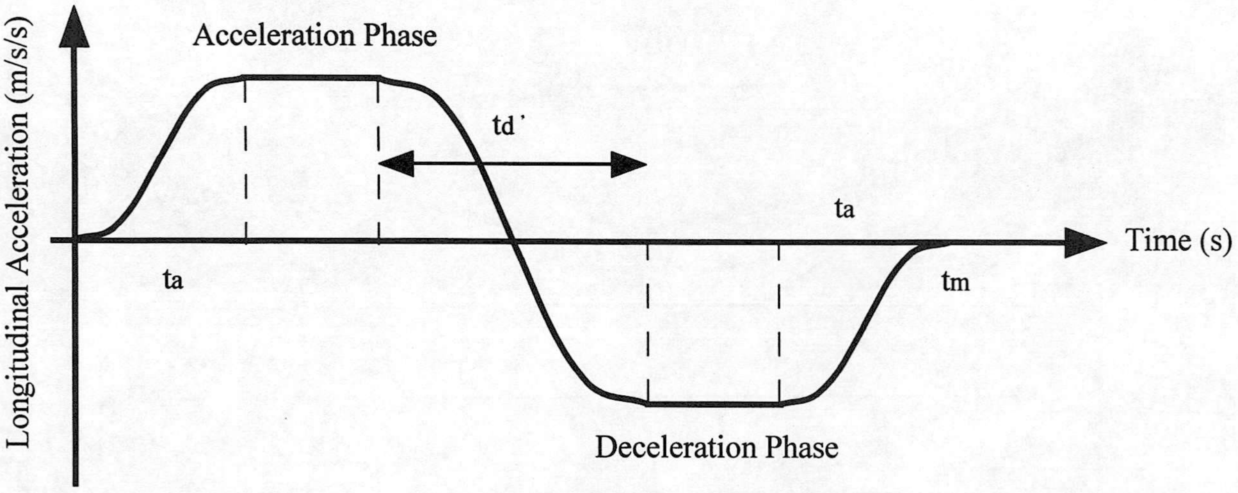


Figure 3.2a: Acceleration profile of Quick-hop Mission Task Element

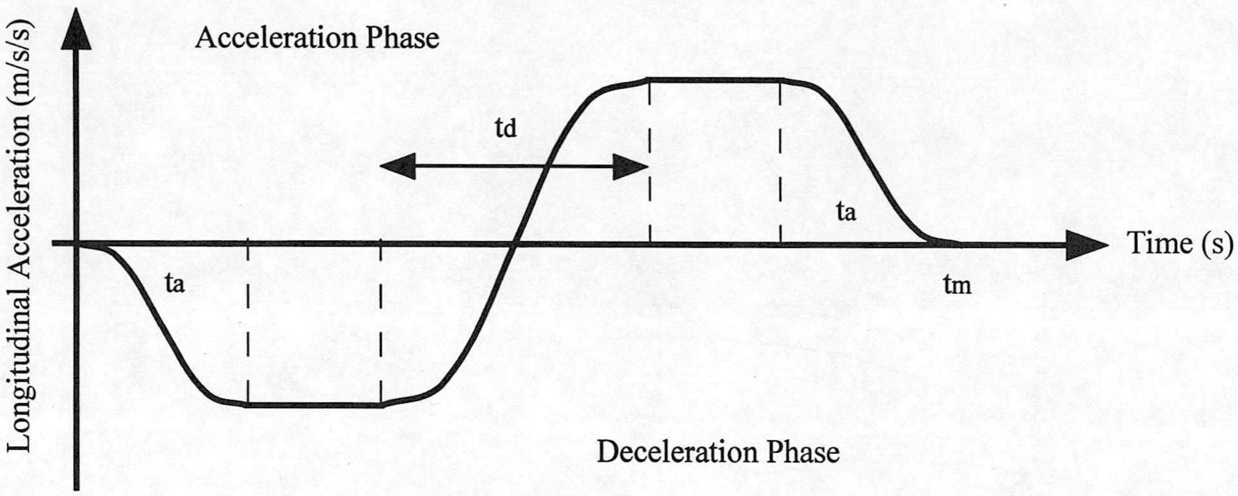


Figure 3.2b: Acceleration profile of Side-step Mission Task Element

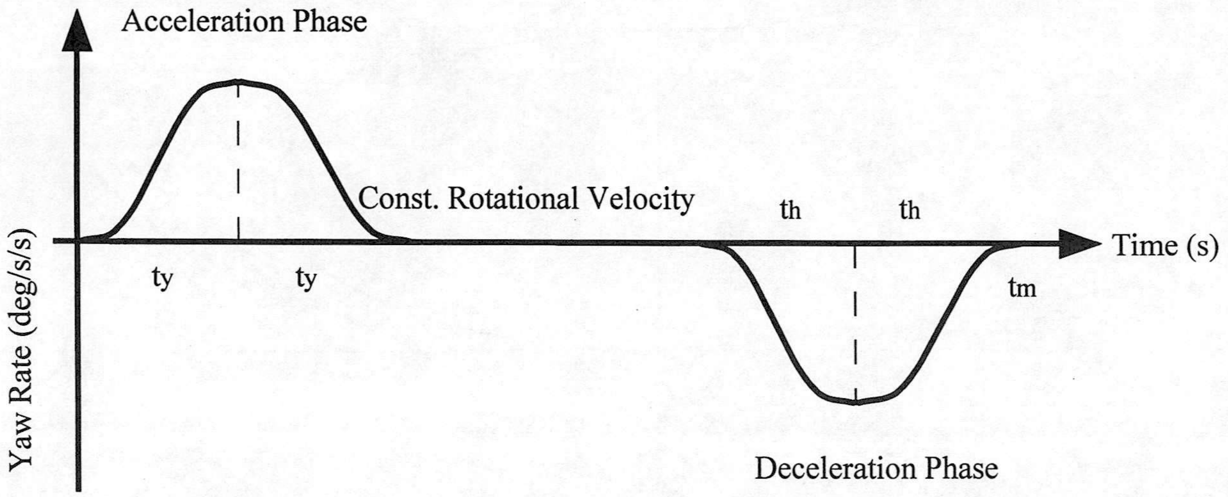


Figure 3.2c: Acceleration profile of Hover-turn Mission Task Element

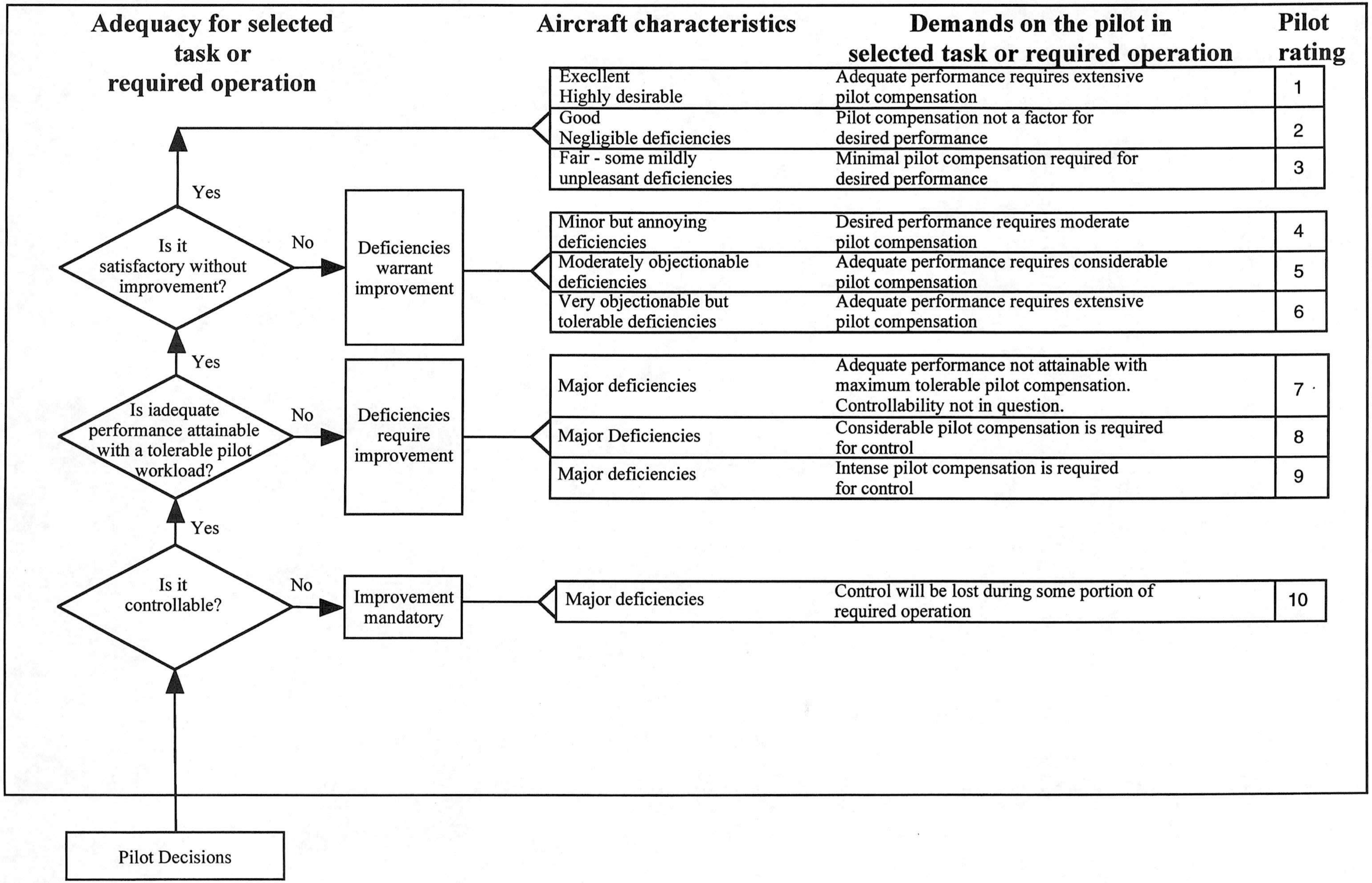


Figure 3.3: The Cooper-Harper Handling Qualities Rating (HQR) scale [1]

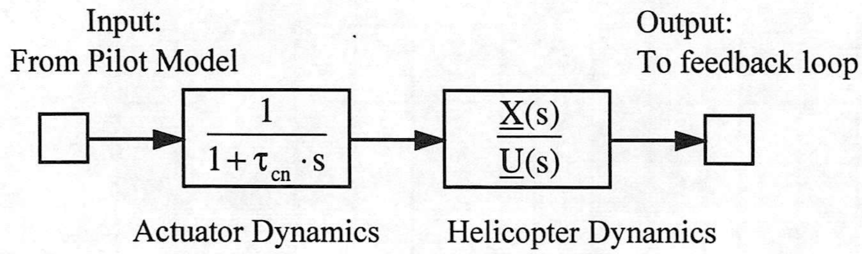


Figure 3.4: Block diagram of actuator dynamics and SISO helicopter model

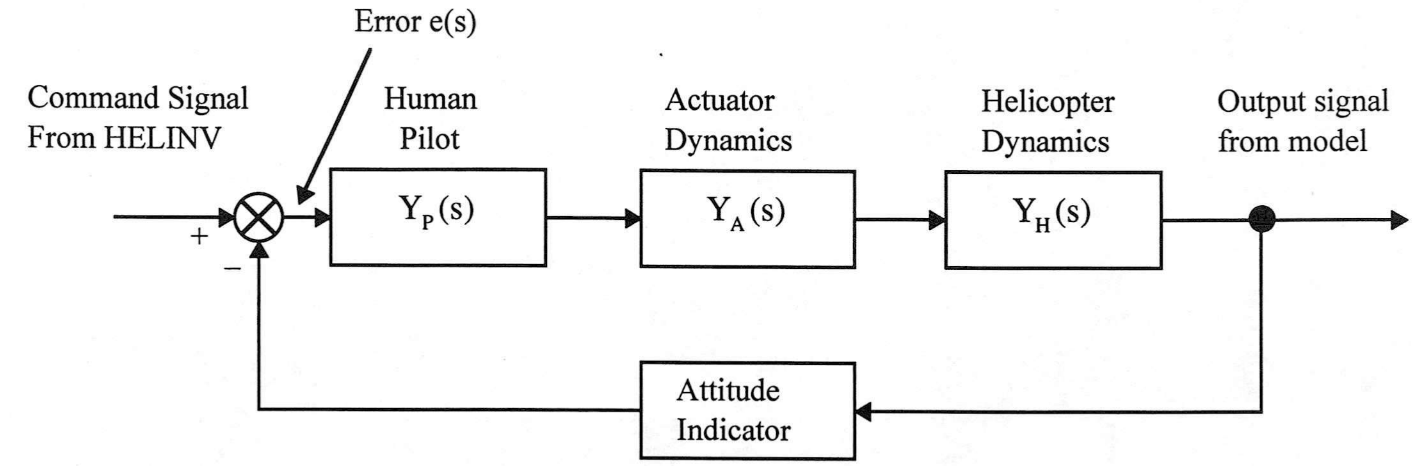
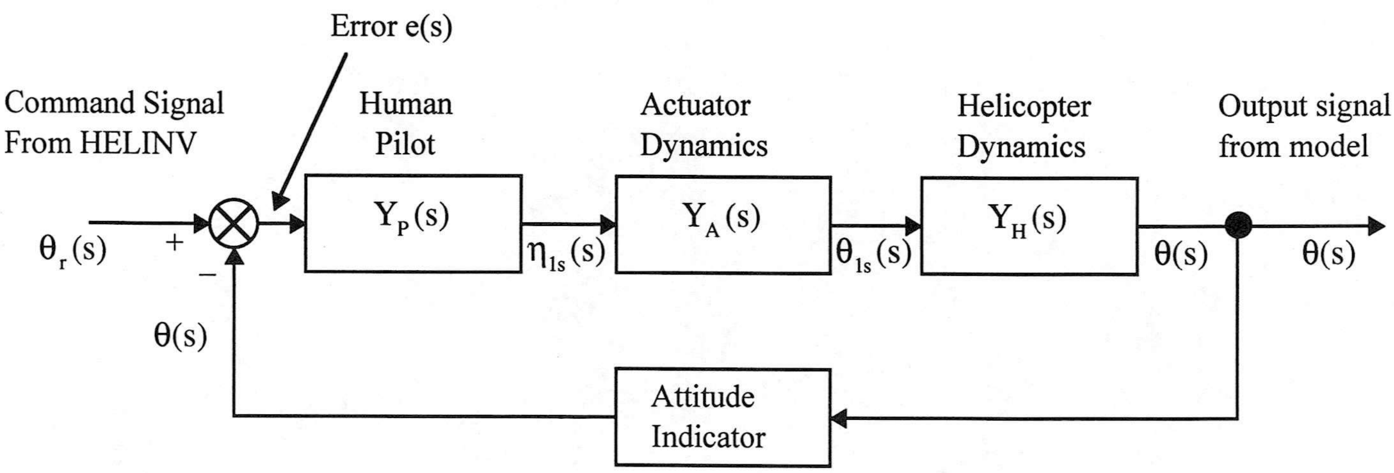


Figure 4.1: Typical single-axis control stystem



where,

$\theta_r(s)$	is the input pitch time-history from the quick-hop MTE
$\eta_{1s}(s)$	is the longitudinal cyclic stick signal from the pilot
$\theta_{1s}(s)$	is the longitudinal cyclic blade pitch of the rotors
$\theta(s)$	is the output pitch time history from the pilot/helicopter system

Figure 4.2: Typical pitch-axis control stystem

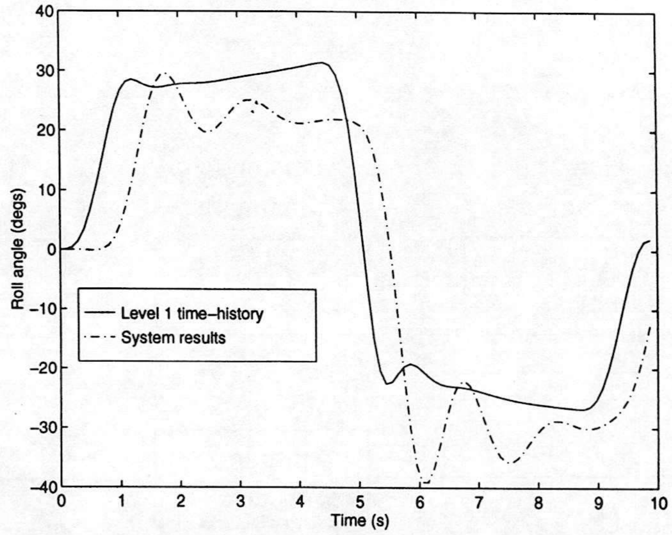


Figure 4.3a: Comparison of HELINV and model results for a Level 1 side-step

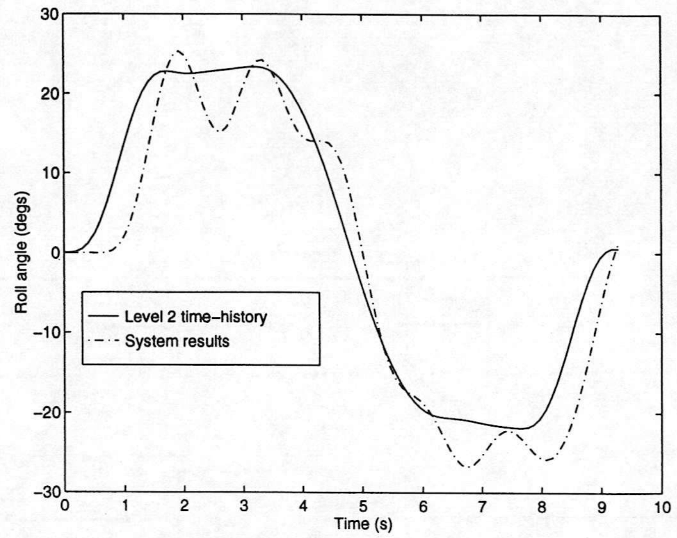


Figure 4.3b: Comparison of HELINV and model results for a Level 2 side-step

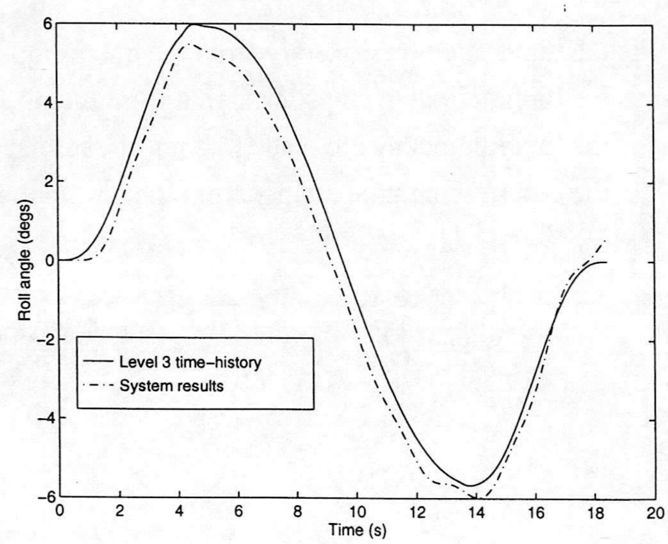


Figure 4.3c: Comparison of HELINV and model results for a Level 3 side-step

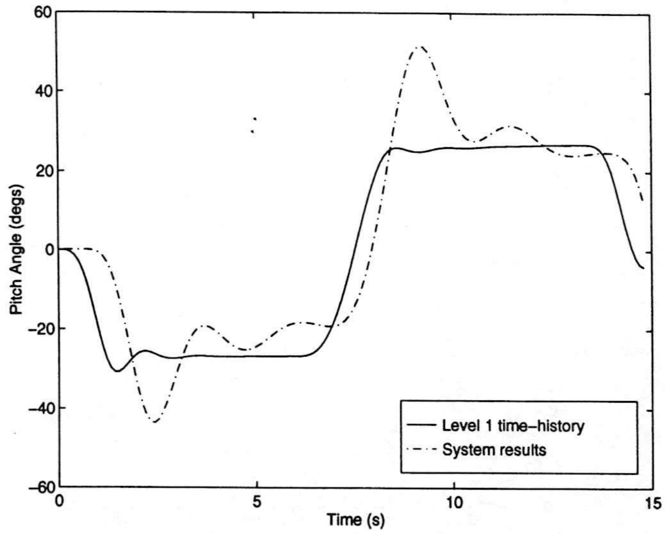


Figure 4.4a: Comparison of HELINV and model results for a Level 1 quick-hop

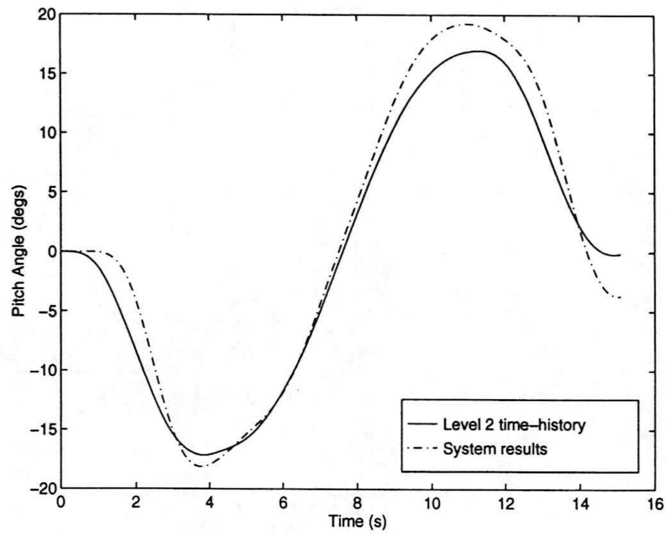


Figure 4.4b: Comparison of HELINV and model results for a Level 2 quick-hop

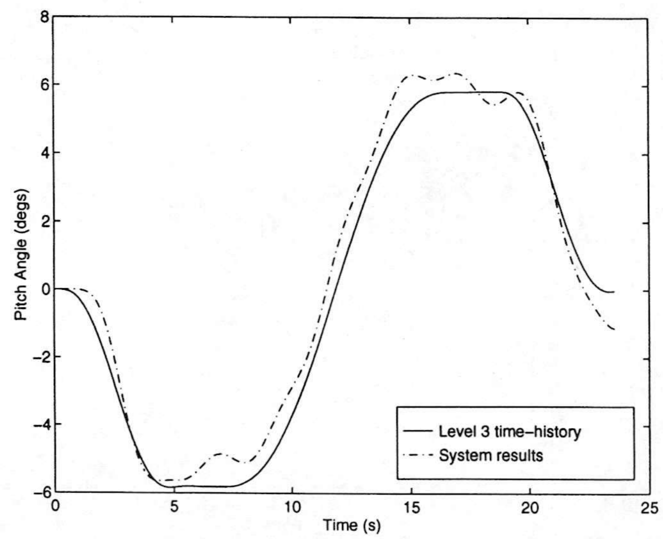


Figure 4.4c: Comparison of HELINV and model results for a Level 3 quick-hop

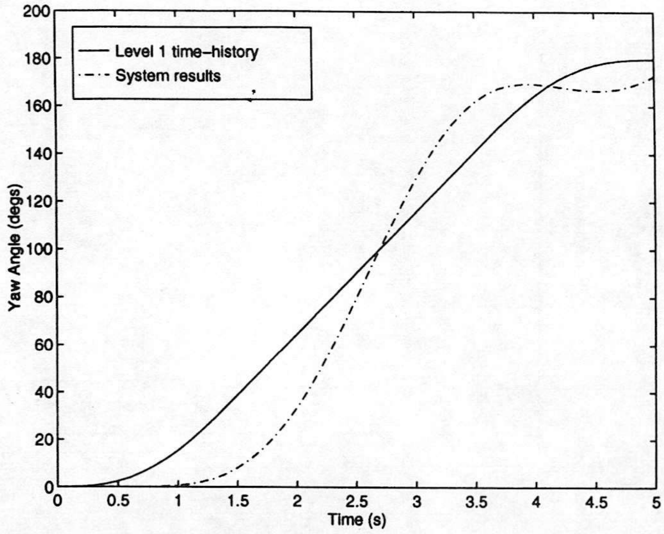


Figure 4.5a: Comparison of HELINV and model results for a Level 1 hover-turn

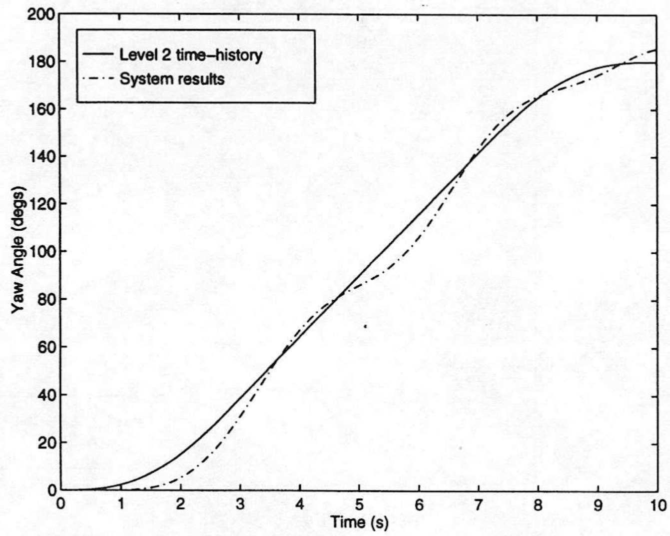


Figure 4.5b: Comparison of HELINV and model results for a Level 2 hover-turn

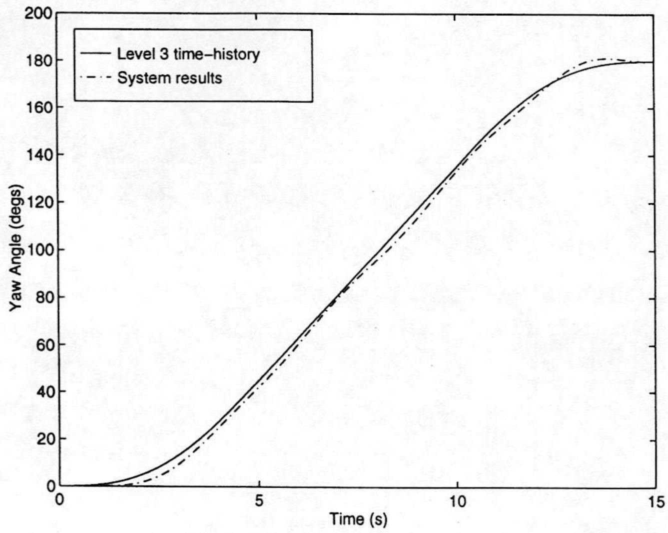


Figure 4.5c: Comparison of HELINV and model results for a Level 3 hover-turn

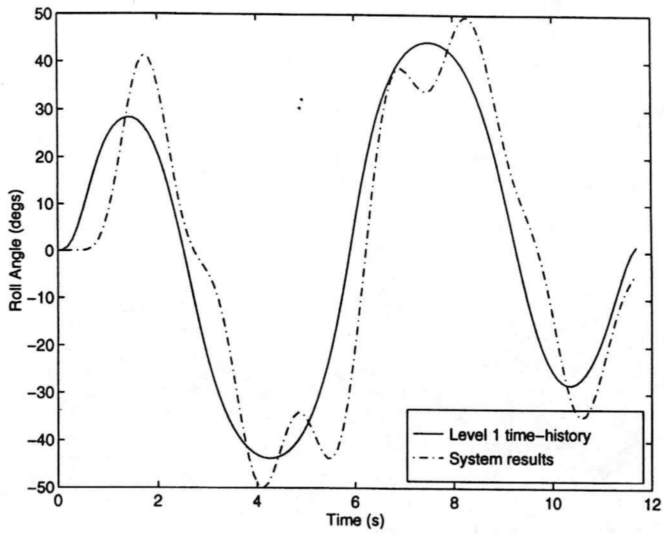


Figure 4.6a: Comparison of HELINV and model results for a Level 1 slalom

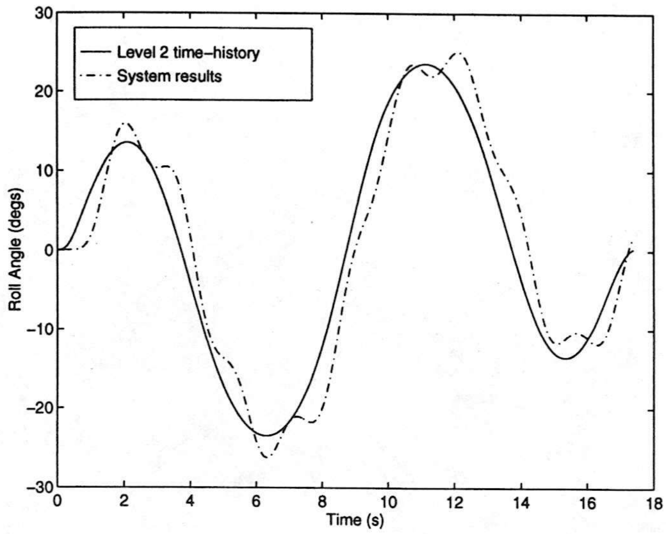


Figure 4.6b: Comparison of HELINV and model results for a Level 2 slalom

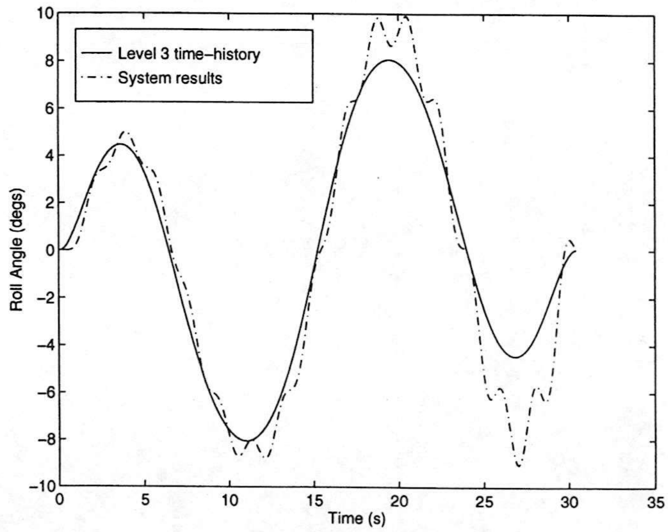


Figure 4.6c: Comparison of HELINV and model results for a Level 3 slalom