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THE USE OF PILOT MODELS IN DYNAMIC PERFORMANCE AND ROTOR LOAD PREDICTION STUDIES

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ABSTRACT

This paper describes the Westland method of using a helicopter engineering simulation, controlled by a pilot model, for dynamic performance and rotor load prediction studies. The reasons for using a pilot model are explained and current and future uses of the models are given. The aims and philosophy of pilot modelling are presented and the method of use for performance prediction studies is outlined; including the methods used to validate the model, and to generate the performance data for inclusion in the rotorcraft flight manual. The structure of the Westland pilot model method is given and the capability of the method is illustrated by examples.

1. Introduction

Helicopter manufacturers are required to promulgate airfield performance data in the rotorcraft flight manual. The data must be based on flight test experience, but some means of interpolating between the test cases is necessary. To generate the data base for all of the conditions required for certification, Westland use an engineering model of the helicopter, controlled by a simulation of the helicopter pilot. The purpose of the computer model is to accurately predict the flight path which a helicopter would follow, when flown to the flight manual technique, in a given set of circumstances. To achieve this, the pilot simulation has to observe the same vehicle limitations and piloting constraints as the human pilot.

The need for dynamic performance models is not new, nor is the method described here. The earliest Westland dynamic performance model, of which I am aware, was used to determine the take-off performance of the Wessex 60 Series 1 in the 1960's. It was written in Elliott Autocode for the Elliott 803 computer. From this first model, a suite of two-dimensional (longitudinal symmetrical) flight path simulations evolved. Programs were written, in FORTRAN, to model the Lynx and Seaking, and numerous manoeuvre specific versions were used during the Westland 30 certification process. By 1985 the code was becoming outdated and expensive to maintain and work was begun on the creation of an entirely new and completely general longitudinal flight path simulation. This was written as a modular program which would lend itself to the simulation of new manoeuvres, by engineers not fully familiar with all aspects of the code. The rotorcraft was fully described by the input data sets and the model was able to simulate any conventional helicopter type, flying any longitudinal manoeuvre. Now known as HAPS - the Westland "Helicopter Airfield Performance Simulation", the program is used for all of Westland's longitudinal flight path prediction work.

Also in 1985, discussions between Westland Helicopters and the Royal Aerospace Establishment (now DRA Aerospace) identified a requirement to study a manoeuvring helicopter rotor. It was decided that a new simulation should be created: to investigate rotor behaviour and performance in manoeuvres, for the prediction of design loads, and to confirm stability augmentation system features. Previously, rotor load cases were run by defining a manoeuvre using a simple simulation model to establish the rotor conditions, and then examining the rotor behavior using a separate analysis program; each condition requiring up to twenty minutes of run time. As the analysis of a complete manoeuvre was a time consuming and expensive procedure, only essential cases could be considered. The proposed new analysis program, which is now known as the Coupled Rotor Fuselage Model, or CRFM, would overcome these difficulties by incorporating a manoeuvre capability, with significant improvements to the rotor analysis program. By coupling the dynamic systems of the rotor and fuselage, using complex rotor modes, the analysis would accommodate the effects of hub motion on rotor load and vibration prediction. As the intention was to analyse manoeuvring flight, an algorithm was required to generate the control inputs to "fly" the simulation through manoeuvres. After reviewing the possible alternatives, the Westland pilot model method was selected, and work was commenced in April of 1989 to extend the logic used in the two dimensional models, to the much more complex task of controlling a full three dimensional simulation. The resulting CRFM pilot model, which is now running but has not yet been validated, is known as the "Helicopter Manoeuvre Simulation Manager" or HELMSMAN. It has been written as a self contained module which accepts vehicle response as input and generates control positions as output. A more complete description of the Coupled Rotor Fuselage Model can be found in references 1 to 4

2. Overview of Pilot Modelling

There are many reasons for using a pilot model. Simulations controlled by pilot models are inexpensive to run, easy to modify, give repeatable results and eliminate the variability inherent in piloted simulations. By removing the human element from the control loop, they obviate the need to run the helicopter simulation in real time; this has several advantages. A simulation which can be run at faster than real time is of great benefit when generating data for the multitude of cases required for flight manual charts. On the other hand, the ability to run at much less than real time is an absolute necessity if you wish to use affordable computers to run complex models; hence the need for a pilot model to control the CRFM for rotor loads predictions in manoeuvring flight. Furthermore, pilot models give the user a clear insight into what is going on. The engineer has full control over the simulation, can change any vehicle or handling parameter at will, and can repeat cases as often as necessary. Because the simulation can be run on a workstation, without the need for a cockpit, pilot, visuals etc., the ability to study manoeuvring flight can be made available to the engineer, at his desk, at very reasonable cost.

At Westland, the Aerodynamics Performance Group use helicopter engineering simulations, controlled by a pilot model, at almost every stage of vehicle development. The suitability of the programs for parametric studies make them valuable tools at the preliminary design stage; for example, when sizing the main rotor for acceptable vertical reject performance. Once flight testing gets under way, the ability to try out handling techniques, and examine the consequences of vehicle limitations, can be used to forewarn the flight crews of any potential problems. Areas of high risk can be analysed in great detail. For this work, the performance prediction simulation is complementary to the piloted engineering simulation. As the vehicle development cycle continues, and certification testing begins, the use of the dynamic performance prediction models becomes intense. At the beginning of the certification process, the models are used to optimise the piloting techniques for best performance. Preliminary charts are produced, as a target to aim for during the certification flying - the benefits of this should not be underestimated. As soon as the handling techniques have been approved, and the model has been validated against the flight test results, the simulation may be used to generate the extensive datasets which will be plotted to produce the dynamic performance charts in the rotorcraft flight manual.

The models have also been found to be highly suitable for research work. The HAPS program was recently used by Westland, in a study for the United Kingdom Civil Aviation Authority (CAA), to examine the engine failure performance of helicopters operating to offshore platforms. An example of a HAPS generated engine failure flight profile is presented in figure 1.

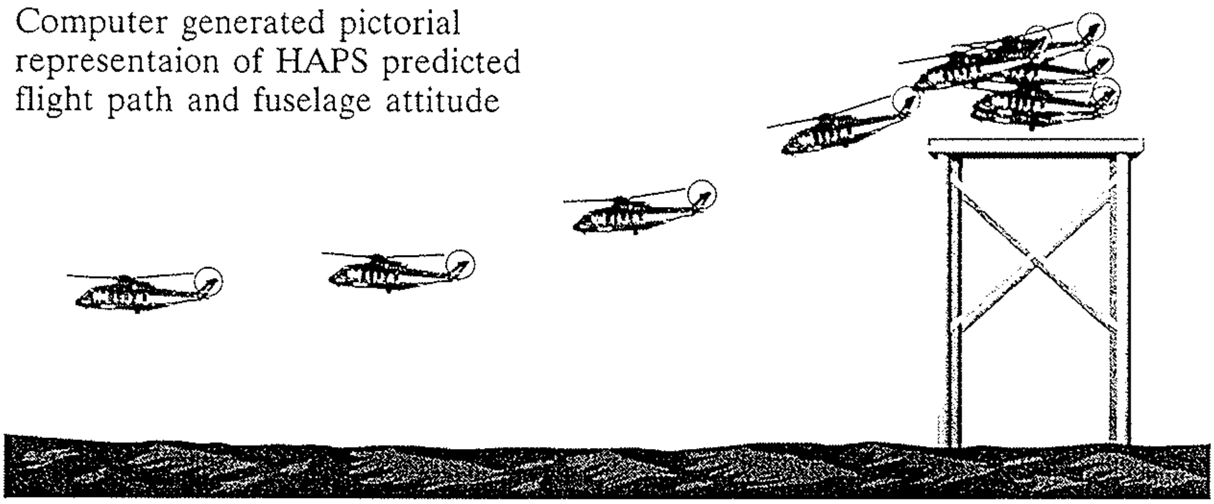


Figure 1 : HAPS predicted offshore platform flyaway.

Earlier this year, HAPS was used to calculate the engine failure performance of the Lynx Mk.9 and it is currently being employed to study the airfield performance of the EH101 in support of the certification program. Both HAPS, and a HELMSMAN controlled blade element model of the EH101, are used from time to time for vehicle development studies; for example, to predict control range requirements, blade lag ranges and transient torque requirements. In the future, the Coupled Rotor Fuselage Model, controlled by the HELMSMAN pilot model, will be used to calculate helicopter dynamic performance, to determine stressing cases, and for the prediction of rotor performance and loads in manoeuvres.

The primary aims in creating pilot simulation models are:

a) To observe all of the vehicle and piloting limitations which would constrain the performance of the vehicle when flown by a human pilot.

b) Thereby to generate realistic flight paths.

3. Method of Use of pilot model controlled simulations for performance prediction studies.

When creating a dynamic performance prediction model, the first action is to create an aircraft input data set for the helicopter and engine combination to be modelled. In the early stages of an aircraft program no flight vehicle will exist, and the most that can be done to validate the model is to compare the steady state power requirements with other theoretical predictions. At this stage the simulation will only be used for preliminary design studies or to make initial performance estimates. When flight testing begins, the aircraft input data set is brought up to date, to incorporate any changes, and to model any special equipment on the test aircraft.

The steady state performance of the model is confirmed by means of a power carpet match and, if available, an analysis of the power breakdown. At Westland we aim to achieve as close a match as possible to the measured power carpet, using the basic power prediction model. Then, for performance prediction work, we use a look up table of correction factors to give an exact match to the measured power carpet. For power available we use a look up table of installed power, obtained by running the engine manufacturer's deck, with allowances for installation losses.

At the same time, consideration is given to the manoeuvres to be flown. The technique required to fly each manoeuvre is analysed and complex manoeuvres are broken down into phases. For each stage of the manoeuvre, the piloting and vehicle constraints and the logic switching triggers are identified and the manoeuvre subroutines are coded and tested. When developing code to define a handling technique it is beneficial to involve a pilot. A workstation with good graphics capability, which can run the simulation and display the vital performance parameters in real time, has been found to greatly reduce the time and cost associated with this task. Experience has shown that the run-time displays should present information in an analogue form which can be quickly and easily assimilated by pilots and engineers. A representation of the cockpit instrumentation and either a simple outside world view or a time history trace has been found to work well (see figure 2). As there is no requirement to include

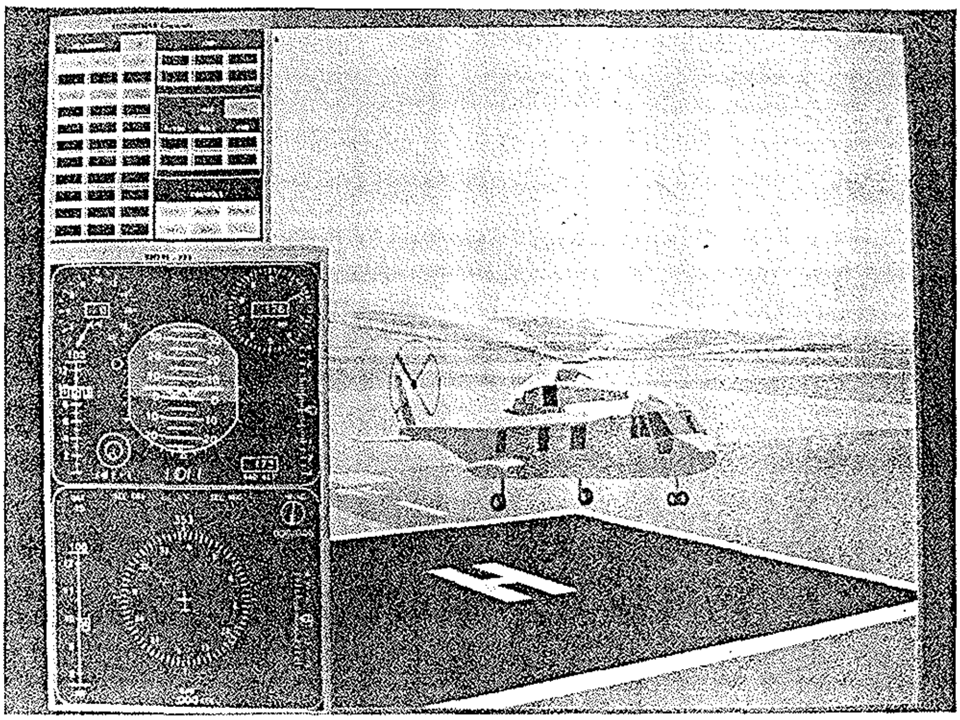


Figure 2 : Interactive display.

the human pilot in the control loop, the specifications for the display resolution and refresh rate are relatively low, which helps to keep the hardware costs down. Once the basic manoeuvre has been programmed, time is spent in optimising the handling technique for best performance. Abuse studies may also be made to check the variability characteristics of the chosen technique and thereby to establish the size of the required safety margins.

Manoeuvre trials are flown to determine the performance of the vehicle and to demonstrate to the certification authorities that the specified handling technique is simple to fly and gives repeatable performance. It is quite likely that, for one reason or another, such as visual cueing or airspeed indicator behaviour, the handling technique will change during the trials and that the final technique, which will be described in the flight manual, will differ slightly from the initially defined technique. For this reason it is useful to have the capability to update the model, and re-issue the target performance charts, during the trials. The move from mainframe computers to workstations which can be transported to the trials site, should make this easier.

With the vehicle steady state performance confirmed by the power carpet match, and measured dynamic manoeuvre results available; the accuracy of the modelling of the vehicle dynamic response, the fidelity of pilot model and the validity of the complete package as a performance prediction tool, can now be verified. The vehicle dynamic response model is validated by comparing the predicted vehicle response to attitude changes and control inputs, with the measured response of the helicopter on flight test. The method is to run the simulation in a matching mode, so that, instead of the pilot model generating the control inputs, the fuselage attitude and collective stick positions measured during the flight trials are fed into the program as input. The resulting prediction of the

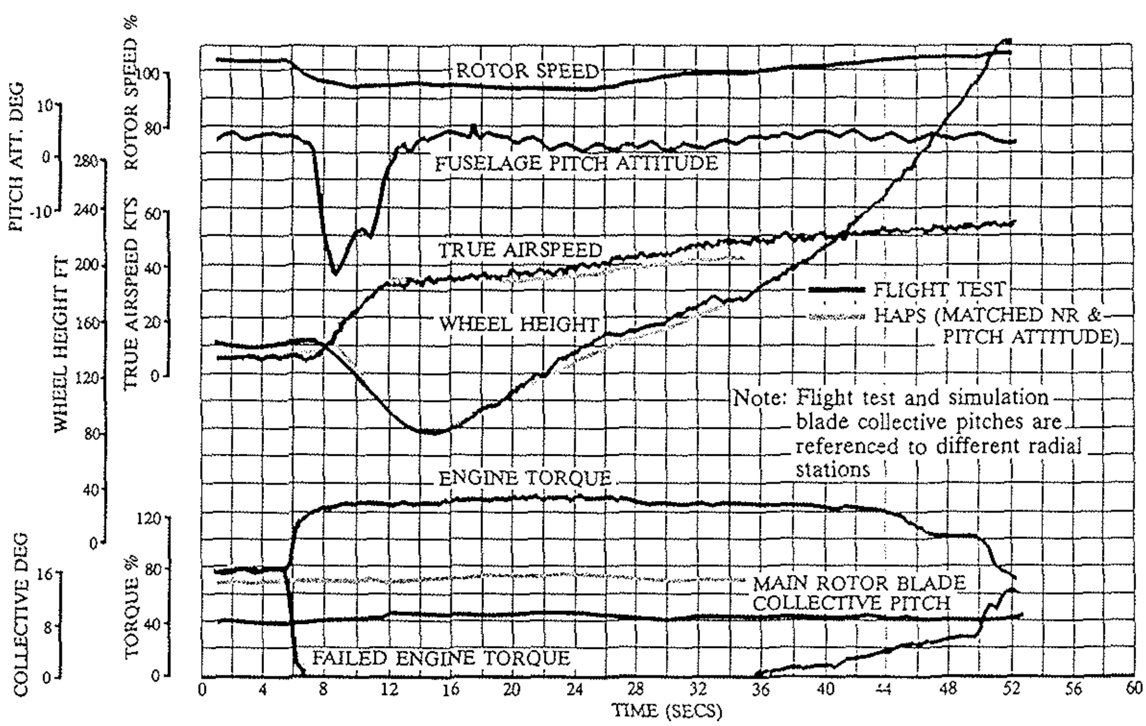


Figure 3 : HAPS matching of a Lynx hover flyaway manoeuvre.

helicopter response is then compared with the measured responses of various key parameters in order to asses the fidelity of the dynamic response model. The comparison is achieved by displaying the measured parameters on a computer screen and overlaying the predicted traces, as they are generated by the simulation. Figure 3 presents a HAPS matching of a Lynx hover flyaway manoeuvre.

It should be noted that, when the simulation is run in matching mode, there is no feedback of vehicle response to the pilot model; the simulation is open loop. Any change in the flight conditions, such as may be caused by variations in wind speed etc., which are not recorded and so are not modelled, will cause the predicted and measured flight paths to diverge. It is necessary, and permissible, for the engineer conducting the matching to make slight adjustments to the input collective and fuselage attitude to compensate for minor variations in conditions. For example, provided the limits of collective travel are not reached, collective may be treated as an internal parameter - it does not limit the performance - in practice, the pilot (and the pilot model) will adjust collective interactively, as required, to sustain some other limiting condition, such as rotor speed or engine torque. Because the simulation does not attempt to model every aspect of the test conditions, the accuracy of the model can only be proved by matching a number of events and checking that none of the parameters show a consistent error - though a certain amount of scatter is accepted as inevitable. Obviously, the higher the quality of the flight test data, particularly the steadiness of the atmospheric conditions, the easier it is to validate the simulation.

Once the steady state and dynamic accuracy of the vehicle model has been proved, the validity of the pilot model must be confirmed. In the first instance, the time history traces produced during the flight trials are analysed to confirm that the handling technique, in terms of the pitch rates and accelerations used, and the speeds and heights at which events are initiated, etc., have been correctly defined. The accuracy of the simulation as a performance prediction tool is then proved by attempting to reproduce the flight test results. The program is run with the pilot model "flying" the simulation to replicate the actually flown technique, (i.e. using the measured attitudes and rates, if they differ from the prescribed technique) and the model is validated by comparing the distances, drop-downs or whatever is relevant, with the measured results.

The model is intended to predict the performance of a helicopter flown exactly to the laid down technique, in ideal conditions, with a steady wind blowing horizontally at the specified strength throughout the manoeuvre, etc. This state of affairs will never apply in practice. The margins required by the certification authorities (wind factors, flyaway ground clearance, rig miss-distances etc.) are intended to allow for variations from the nominal conditions. When developing techniques, the predicted scatter in performance, due to technique abuse and other factors, must not be bigger than the relevant safety margins. The corollary, is that the margins set by the certification authorities, should be a function of the repeatability of the manoeuvre. If the margins are significantly larger than are required for safety, the helicopter's payload will be unnecessarily restricted. It is important therefore, that the handling technique laid down in the flight manual can be repeatably flown by a pilot of average ability, i.e. that small amounts of technique abuse do not have a significant affect on performance. The ease of flying the technique is evaluated by the company and certification test pilots. The repeatability of the technique is one of the factors which is looked for when testing, and when validating the complete model. The ideal is for the predicted performance to lie close to the centre of a small scatter band of flight test results. A significant benefit of using a pilot model is that it is a relatively simple matter to conduct the necessary parametric studies to check the consequences of technique abuse.

Only when the flight testing and computer validation tasks are complete, and the certification authorities are satisfied that the simulation accurately represents the performance of the aircraft, may the program be used to run the multitude of cases required to create the dataset which will be plotted to produce the dynamic performance charts in the rotorcraft flight manual. For this work the graphics capability of the model is not required and is switched off. The simulation is set up to run as a background task - often over night - and will calculate the performance for every required combination of aircraft weight, altitude, temperature, wind speed, and obstacle height, etc. A separate suite of computer programs is then used to plot the simulation output data.

4. Structure of the Pilot Model

Both the HAPS pilot model and the CRFM HELMSMAN are modular computer programs written in FORTRAN, with PHIGS graphics subroutines for visualisation. The logic is intended to mimic the thought processes and actions of a human pilot. The pilot model is called at each time step of a simulation run and, using position and rate information from the vehicle model as input, it calculates the control movements required to achieve a specified piloting task. A separate channel of logic is used for each pilot controllable axis, i.e the pilot model considers the pitch, roll, yaw

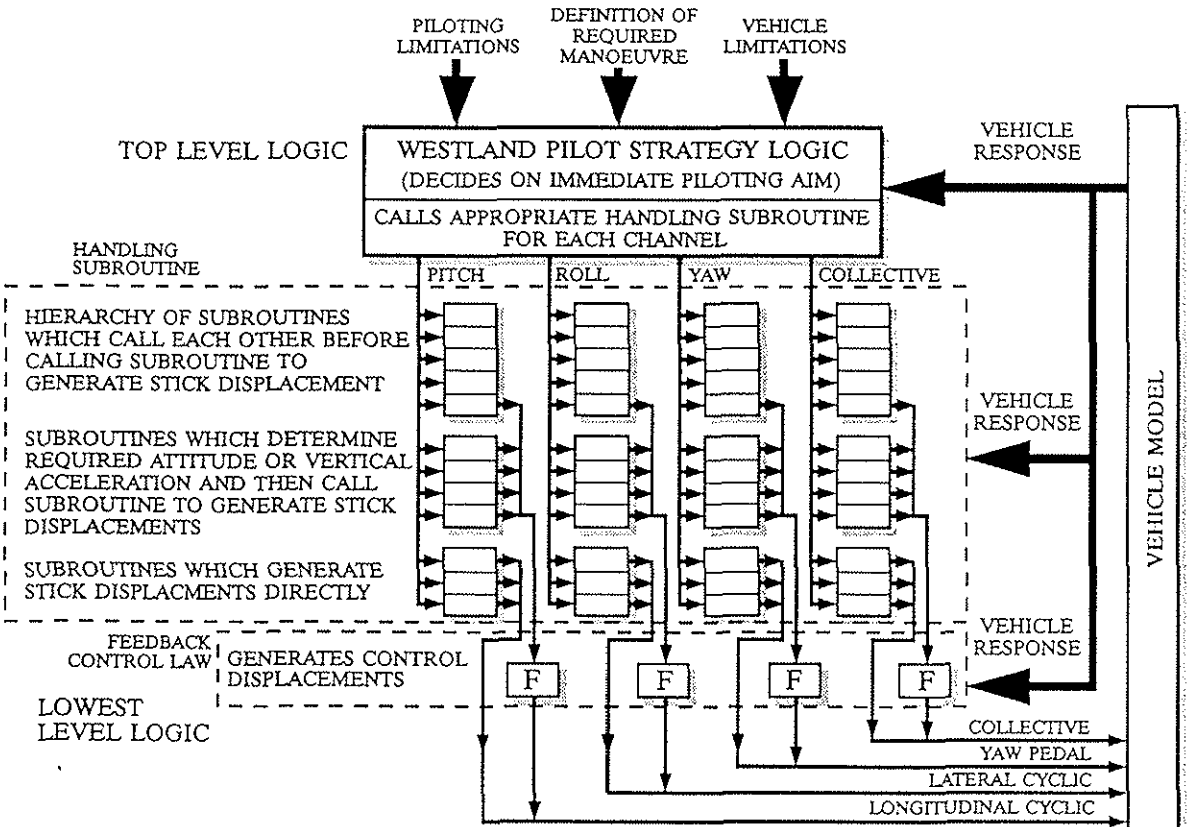


Figure 4 : HELMSMAN logic flow and calling sequence.

and collective inputs independently. The pilot model adapts to changing circumstances and observes any relevant vehicle or piloting limitations. If the immediate piloting goal cannot be achieved without exceeding a constraint, the pilot model will amend the manoeuvre in a logical way.

The Westland pilot models simulate the activity of a helicopter pilot at three levels. The top level of the logic can be thought of as modelling the conscious decision making activity of the pilot. At this level the pilot knows what the object of the exercise is, and forms a strategy by which the desired end result may be achieved. The strategy is implemented by setting a series of immediate piloting goals, such as achieving a particular speed and rate of climb. Goal switching occurs as a manoeuvre develops or in response to unscheduled events. For example the logic will switch as each sub-task is achieved and in response to an engine failure or torque limit exceedance. At the second level, the logic models the sub-conscious activity required to achieve the immediate piloting goal set by the top level logic. If the top level logic sets the goal of flying in a particular direction, the second level logic will specify what the present roll attitude should be, in order to go from the current heading to the target heading. The lowest levels of the logic can be thought of as modelling the instinctive "stick and rudder" motor skills of the pilot. These subroutines generate the control displacements required to achieve the required attitude, torque, rotor speed etc. See figure 4.

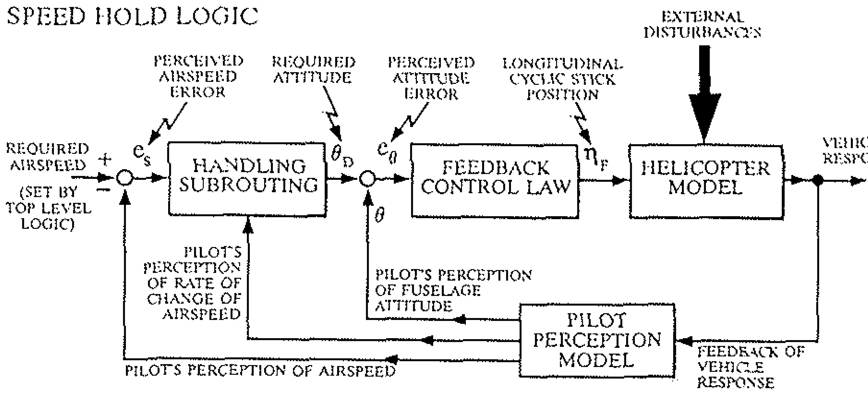
What follows is a description of how the pilot model is implemented - starting with the lowest level subroutines and working back up to the top level logic.

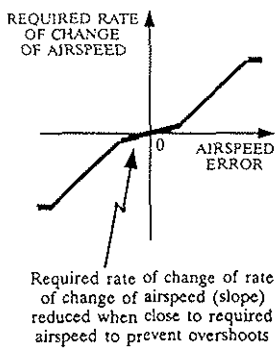
The lowest level subroutines are simple feedback control loops which use error signals to generate a control deflection which, when input into the helicopter model, will result in a vehicle response which tends to reduce the original error. The feedback control laws generally consist of a proportional term for good transient response, and an integral term to eliminate steady-state errors. An error rate term and/or an attitude rate term is sometimes used to to improve the stability.

The lowest level feedback control algorithms are called by handling subroutines. Each handling subroutine has been written to achieve a specific piloting task; they are the main modular building blocks of the pilot simulation model. The handling subroutines combine open loop and closed loop algorithms, and they are called both by the top level logic and by each other. For example, three separate subroutines have been written: to attain and maintain a specified vertical acceleration, vertical speed, and height. They may each be called directly from the top level logic to generate the collective control inputs required to achieve the relevant flight condition. The vertical acceleration subroutine uses a feedback controller to adjust the collective pitch so as to achieve the required vertical acceleration. The vertical speed subroutine uses an open loop controller to specify what the target vertical acceleration should be, in the next time step, in order to smoothly attain the required vertical speed. The vertical velocity handling subroutine then calls the vertical acceleration subroutine to generate the required collective control input. Similarly, the height hold subroutine specifies the vertical speed required as a function of the height error and then calls the vertical speed subroutine, which in turn calls the vertical acceleration subroutine, which generates the control input. As another example, consider the operation of the subroutine to attain and hold a specified airspeed. In this case the logic adjusts the target pitch attitude in response to the rate of change of airspeed and then calls one of the lowest level subroutines to generate the longitudinal cyclic stick displacement required to match the helicopter's attitude with the target value. The maximum pitch attitude, pitch rate, and pitch acceleration values to be used in attaining and holding the speed are input as data items. The operation of the logic is illustrated and explained in figure 5.

The top level of the logic consists of a suite of manoeuvre specific subroutines. Each of the top level logic subroutines monitors the progress of a manoeuvre, observes the vehicle and piloting limitations, and sets the immediate piloting goals. The logic attempts to achieve a specified end result, as programmed by the user. The purpose could simply be to turn onto a heading at a given rate and airspeed; or it could be to land on an offshore platform, on a gusty day, with an engine failure at the landing decision point. As with the handling subroutines, the top level logic subroutines can be written as modules, so that very complex manoeuvres can be modelled as a sequence of simpler events. The HELMSMAN and HAPS models

SPEED HOLD LOGIC





- The Handling Subroutine:
  - Uses a feedback controller to determine the required pitch rate as a function of the perceived error in the rate of change of airspeed
  - Checks that the proposed pitch acceleration and pitch rate do not exceed the piloting limits set for the manoeuvre
  - Integrates to find the target attitude required for the next time frame
  - Checks that the proposed attitude does not exceed the piloting limits set for the manoeuvre
  - Calls a low level handling subroutine to calculate the stick displacement required to minimise the attitude error

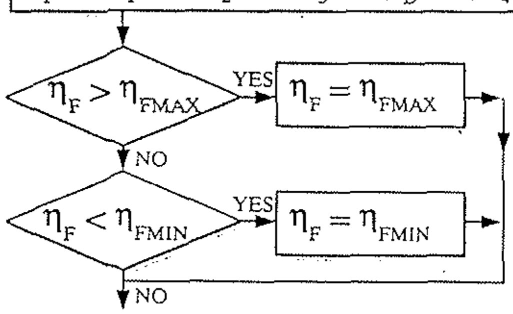
OPERATION OF FEEDBACK CONTROL LAW LOGIC :

$e = \theta_D - \theta$ (- Error term)

$\dot{e} = (e - e_p)/\Delta t$ (- Error rate term)

$\bar{e} = \bar{e} + e.\Delta t$ (- Integral term)

$\dot{\eta}_F = ek_1 + \dot{e}k_2 + \bar{e}k_3 + (\dot{\theta}_D - \dot{\theta})k_4 + \ddot{\theta}k_5$



$\ddot{\theta}$ term only invoked when S.A.S. is switched OFF - improves pitch damping

Figure 5 : Pilot model subroutine logic.

attempt to fly the desired manoeuvre as accurately as possible but, like a human pilot, the pilot model will modify, or even abandon the manoeuvre if vehicle or handling limitations are exceeded. Consider the case of an engine failure on take-off - the "all engines operating" technique will be flown up to the moment of engine failure recognition (which could be some time after the event, to allow for the pilot intervention delay time) - the piloting goal will then change, and the top level logic will either execute an OEI continued take-off or landing. More subtly, the logic will modify a manoeuvre to observe a vehicle limitation. In a steeply banked turn, the pilot model will modify the manoeuvre to observe "g" limits or engine torque limits. In this case the pilot model will not fly the manoeuvre exactly as specified; the speed or height may be allowed to vary in order to observe the more critical limitations. The flight path generated by the model will however be realistic and will be close to that which a human pilot would have to follow in practice.

HAPS and HELMSMAN read in all of the manoeuvre specific simulation parameters as data items. When executing a take-off, for instance, the aircraft weight, the wind speed, the take-off decision point (TDP) height and the target speeds etc., can all be varied without making any changes to the computer code. To generate the data for the creation of the flight manual charts, the simulation is run repeatedly, with each parameter incremented in turn. All of the relevant input and output parameters are automatically recorded for each condition, and are written to a file ready for plotting.

5. Pilot Model Capability

The CRFM HELMSMAN is still under development but, to illustrate the current capability of the model to control helicopter simulations, a demonstration manoeuvre has been programmed - see figure 6. A black and white representation of the colour interactive display seen by the user, was given in figure 2. For demonstration purposes, the vehicle model used here is not the complex CRFM, but a simpler blade model normally used on

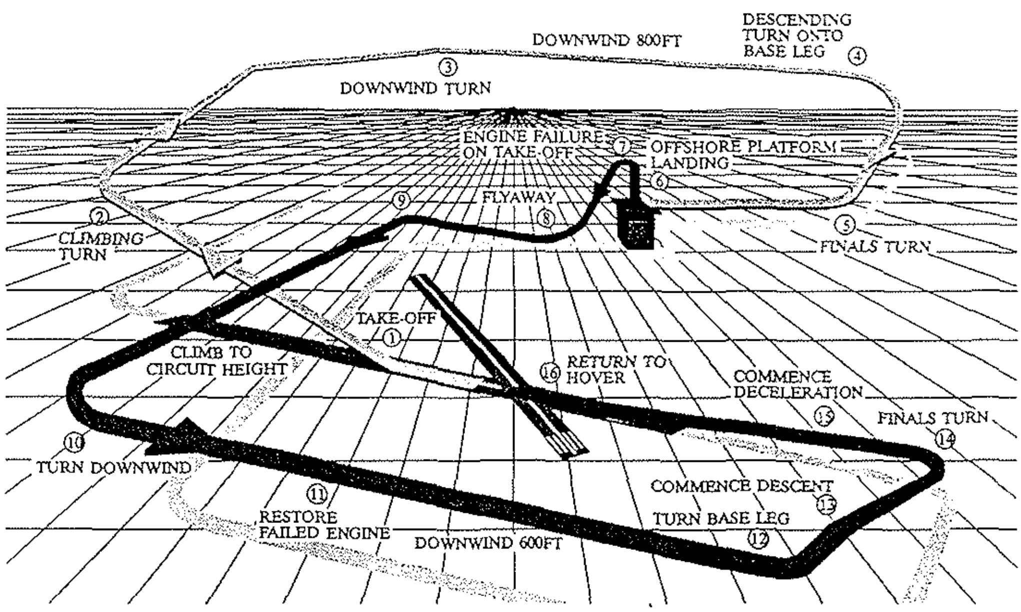


Figure 6 : Demonstration Circuit.

the piloted EH101 engineering simulation. The demonstration begins with the helicopter in the hover above a runway. A take off is performed and the helicopter is flown around a right hand circuit to approach and land on an elevated helideck using an offshore platform technique. From the hover above the deck, an offshore platform take-off is performed, with an engine failure recognised just after the TDP leading to a flyaway. The pilot model then takes the aircraft around a left hand circuit, restores the failed engine and flies a normal "all engines operating" approach to the runway; returning to the hover at the point where the demonstration began. A time history trace for the demonstration circuit is given in figure 7. The circuit height, bank angles, pitch and roll rates, ground tracks, wind speed, etc., are all data items which can be varied. The numbered events on figure 7 refer to the numbered positions marked around the circuit shown on figure 6.

When used for rotor load prediction studies, the CRFM/HELMSMAN will model manoeuvres of much shorter duration than demonstrated above. For example to model limit load cases the pilot model will manoeuvre to achieve a specified flight condition. Performance prediction studies will involve elements of the demonstration manoeuvre, such as the take-offs and landings. There are other possible applications however, such as the prediction of noise footprints, where elaborate manoeuvres, similar to the full demonstration, may be required.

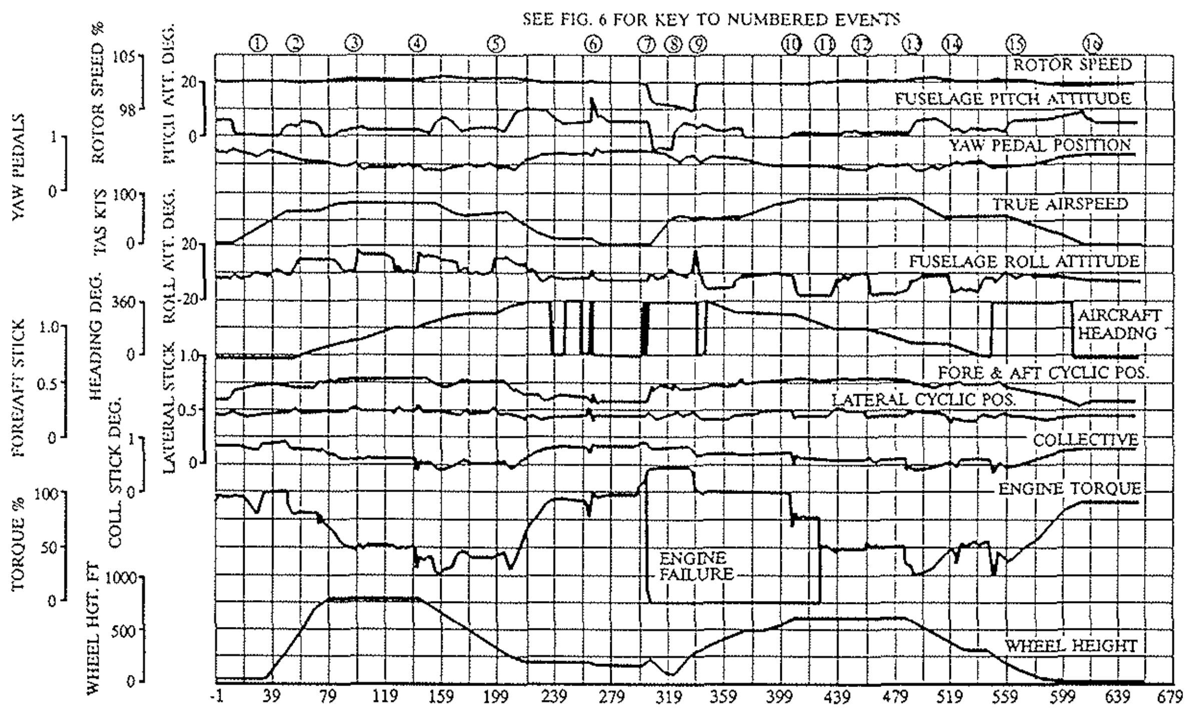


Figure 7 : Computer generated time history trace for demonstration manoeuvre.

6. Conclusions

Westland use helicopter engineering simulations, controlled by pilot models, for rotor loads and performance prediction studies. The method has several significant advantages.

Pilot models generate realistic flight paths, which can be exactly repeated as many times as necessary; the models are therefore ideal for parametric and technique abuse studies. Pilot model controlled simulations can give the user a very clear insight into what is going on - the engineer can analyse an event in detail, and knows, all of the time, exactly what the "pilot" is "thinking" and doing.

Because a human pilot is not included in the control loop, it is not necessary for the helicopter simulation to run in real time - performance models may be run faster than real time for chart data production, and complex models may be run at less than real time for such things as rotor load prediction studies. By making it possible to run complex models on low cost workstations, the method makes helicopter engineering simulation affordable.

At Westland, the 2-D HAPS program is used for vehicle design and development work, for predicting the helicopter's dynamic performance prior to testing, and to produce the data for *flight manual charts*. The three-dimensional CRFM will be used for rotor and vehicle design work and, in a simplified form, for dynamic performance prediction studies.

Acknowledgements

The HAPS and HELMSMAN programs are the result of many years of development by my predecessors in the Aerodynamics Department at WHL. I would like to acknowledge the particular contributions of M. Hughes, who originated the HAPS programme, my colleague G. Matthews who is responsible for many recent enhancements, and D. Swabey whose skill with PHIGS is self evident. I am also grateful to F.J. Perry and R.E. Hansford for valuable suggestions and to Westland's test pilots, in particular J. Tracy, for thoughtful explanations and practical demonstrations of piloting techniques.

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