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OP 05
A Methodology for the Prediction of Pilot Workload and the influence on Effectiveness in Rotorcraft Mission Tasks

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ABSTRACT

The paper provides an overview of a new methodology for the prediction and estimation of pilot workload and the influence on effectiveness in rotorcraft mission tasks. The approach integrates contributions from several substantial individual research activities including inverse simulation, wavelet-based control analysis, exceedance/rule-based prediction and probabilistic handling qualities metrics. The method is focused on the primary piloting function with the aim of providing a cost effective tool, using off-line simulation and analysis, for assessing the impact and effectiveness of piloting aids on rotorcraft mission peformance. The method is intended for exploitation in support of the requirements capture, competitive assessment and preliminary design phases of procurement. In the paper the elements of the methodology and selected results will be presented to highlight progress and demonstrate how off-line predictions compare favourably with data from piloted experiments. Sufficient progress has been made with each of the individual aspects, and their integration, to assert confidently the feasibility of predicting workload ratings and metrics of practical value during early phases of procurement and design, using aircraft configurational information and outline mission requirements. The future direction of the research will also be briefly discussed.

1 INTRODUCTION

A programme of research has been undertaken by the Defence Evaluation & Research Agency (DERA) with support from Glasgow Caledonian University (GCU) and the University of Glasgow (UG) to develop a methodology for the prediction and estimation of pilot workload and the influence on effectiveness in rotorcraft mission tasks. The methodology is centred on the primary piloting function and is intended to provide a cost-effective means for supporting the optimisation of rotorcraft piloting aid systems through off-line simulation and supporting data analysis techniques.

Several technical areas are integrated into the overall methodology. Inverse simulation (Ref. 1) is used to generate control and vehicle dynamic responses for defined manoeuvres that emulate flight test manoeuvres taken from the Aeronautical Design Standard ADS-33 (Ref. 2). Comparisons are then made with the control strategy observed in data collected from piloted flight and simulation trials. The response data is analysed using both frequency and time domain techniques with particular emphasis on the adaptive wavelet reconstruction (AWR) (Ref 3, 4) process for the extraction of metrics for correlation with workload ratings. In another development, a probability analysis of pilots' handling qualities ratings from trials evaluations has shown potential as a basis for mission effectiveness criteria (Ref. 5).

A key intermediate step in the methodology is the development of criteria for assigning workload ratings based on the metrics that are output from the adaptive wavelet analysis. This new work, supported by correlation with subjective pilot ratings and opinion, is a crucial link in the process. These ratings are comparable with the established Cooper Harper scale (Ref 6) but since they involve only the pilot's control strategy, the terminology *control workload rating* is employed in order to clarify the distinction.

The aim of this paper is to give an overview of the methodology, its potential applications and future development. Section 2 of the paper discusses the background and principal objectives of the research; section 3 provides an outline of the methodology and its key components; section 4 presents some of the development activities undertaken in specific areas of the methodology, and their current status. Finally, in sections 5 and 6, a review of future developments and summaries of the main conclusions and recommendations are presented.

2 BACKGROUND AND OBJECTIVES

The ultimate objective of the research is to develop an off-line desk-top methodology for prediction of pilot workload in rotorcraft mission tasks. The motivation for the project was the perceived need for a low cost approach to evaluation of flight control system concepts to support the exploitation of new developments such as active control technology (ACT). Earlier research had shown that the performance and achievable effectiveness in the current generation of military helicopters is often spoiled by poor handling qualities, but that improvements could be made through the introduction in future types of either full or partial-authority ACT (Ref. 7). However, a number of important handling qualities issues need to be addressed to identify optimum configurations, the resolution of which inevitably incurs a considerable overhead in flight trials evaluations. Exploitation of both off-line and real-time piloted simulation were seen to offer the potential for reducing this dependency in future procurement activities. Hence, the aim was to develop modelling assessment methods for addressing handling and associated pilot workload issues at the conceptual stage early in the specification and design cycle and predicting high piloting workload situations before they are 'discovered' in flight.

In previous work (Ref. 8) the HELINV (Ref. 1) implementation of helicopter inverse simulation had successfully demonstrated its capability for identifying handling qualities 'cliff edges' - manoeuvre situations where piloting workload increases to the point where the task cannot be completed and/or loss of control can occur. Inverse simulation was, therefore, considered to be a suitable approach for generating control responses from which workload metrics could be extracted using adaptive wavelet techniques. The metrics would then be converted into workload ratings by the application of validated evaluation criteria.

The aim was to develop the evaluation criteria through correlation of the metrics with objective and subjective data from flight and simulation trials, including Cooper-Harper handling qualities ratings (HQRs). Data, in the form of control displacements, vehicle responses, flight path co-ordinates and pilot's HQRs, were generated specifically for this purpose through piloted evaluations using the DERA's Lynx research helicopter and Advanced Flight Simulator (AFS) (Refs 9,10,11). The tests involved handling qualities assessments of different aircraft and model configurations in both ADS-33 style flight test and simulated mission evaluations. The latter comprising a continuous nap-of-earth (NOE) flight sequence with embedded role related tasks such as Bob-up to visually acquire and track a moving target.

3 THE WORKLOAD METHODOLOGY AND ITS DEVELOPMENT

In this section of the paper, an overview of the methodology, its development and intended application is given. In advance of this discussion, since the ADS-33 handling qualities approach has played a key role in both the design and the development of the workload methodology, a brief overview of those aspects of ADS-33 that have a particular relevance is given.

3.1 Influence of ADS-33:

ADS-33 represents a mission-orientated handling qualities specification with a framework that take into account: operational manoeuvre demands in the form of 'mission task elements' (MTEs), the nature of the vehicle response to control inputs or control response type, and visual conditions or 'useable cue environment' (UCE). These are combined to form a set of requirements which specify the dynamic response criteria and level of control augmentation required for specific operations in given levels of visibility. The Cooper-Harper scale, see Fig 1, is used as the basis for defining 'acceptability' standards regarding levels of pilot workload and handling qualities, where the following levels are defined:

Level 1: Ratings 1-3 Aircraft characteristics satisfactory; desired performance achieved with minimal pilot compensation & low workload.

Level 2: Ratings 4-6 Aircraft characteristics unsatisfactory; desired performance requires moderate pilot compensation (Rating of 4), or adequate performance requires considerable to extensive compensation (Ratings of 5-6).

Level 3: Ratings 7-9 Aircraft characteristics unacceptable; adequate performance unattainable with tolerable pilot workload. For ratings 8-9, loss of control is threatened; a rating of 10 signifies actual loss of control at some stage of the task.

In ADS-33, an MTE is defined as 'an element of a mission that can be treated as a handling qualities task'. For a given operational role, a typical flight or mission comprises a contiguous sequence of events, which may be broken down into component flight and task phases and their characteristic manoeuvres, or MTEs. In this way, the MTEs provide a basis for categorising the manoeuvre demands throughout the operational flight envelope, in relation to piloting control strategy and demands on vehicle dynamic performance. Hence, the ADS-33 criteria and associated open-loop testing provide the basis for assessing or predicting the handling qualities of a given configuration in a given role. To ensure the best possibility of an accurate assessment, a further set of MTE-based flight test procedures are specified for the purpose of awarding assigned handling qualities, through subjective evaluation. It is this emphasis on performance and workload in realistic, mission oriented tasks, that must be carried through into a nonpiloted simulation environment in order to achieve the objectives of this programme of research. For brevity in the remainder of this paper, the term MTE corresponds to ADS-style flight test manoeuvres and associated evaluation procedures.

3.2 Methodology:

The evaluation methodology follows the sequence:

(i) Computation of control and vehicle responses from simulations of a specified aircraft model and set of MTEs,

(ii) Extraction of appropriate evaluation metrics by the analysis of control and vehicle responses,

(iii) Application of 'rating' criteria to the metrics,

(iv) Application of effectiveness criteria to derived ratings.

For item (i), there exists a substantial body of experience in the use of inverse simulation for performance and handling qualities studies, and the enhancements undertaken for the current programme of work are discussed in section 4. Items (ii) and (iii) were regarded as critical to the success of the methodology and, hence, they have provided the main focus for the research. Continuing the analogy with the ADS-33 approach, a particular aim was to develop an 'equivalent' HQR rating procedure, based on the

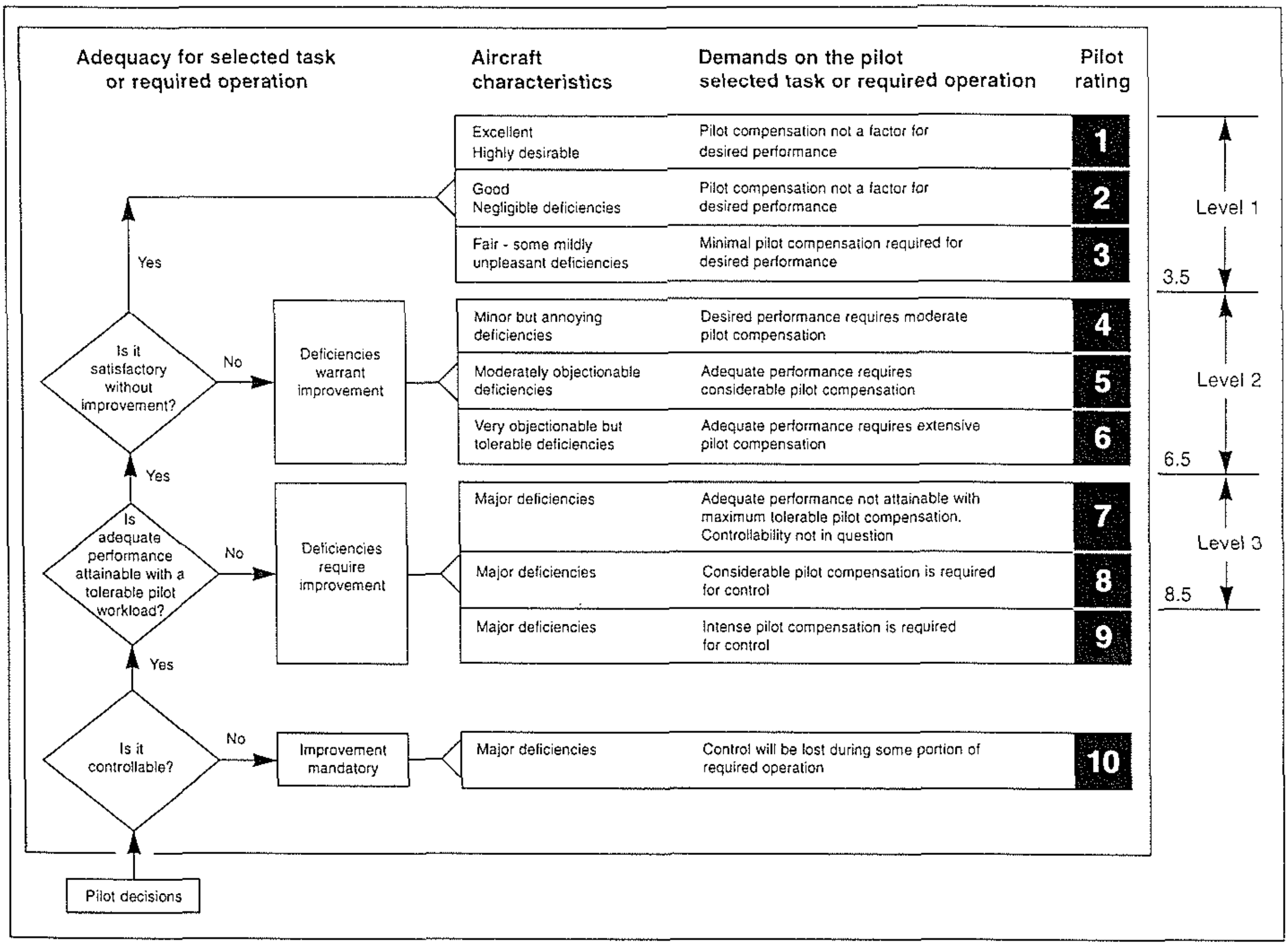

Fig 1. Cooper-Harper Rating Scale for Handling Qualities

assessed control workload in a given task. HQRs are determined according to the pilot's perception of task performance, task workload and system characteristics. For an inverse simulation-based assessment, the predicted control strategy provided a potential basis for quantifying the compensatory control workload component of an HQR, in the form of a control workload *rating*. For item (iv), the aim was to translate such ratings into specific mission effectiveness metrics. Some approaches that have shown promise in addressing these aspects are discussed in section 4.

3.3 Inverse simulation:

In effect, HELINV performs an off-line version of the MTE evaluation procedure, providing a means for predicting control strategy and vehicle responses for a given manoeuvre. HELINV incorporates an algorithm for generating specified ADS-33 MTE related flight path kinematics in a suitable format for input to the solution algorithm (Ref 12). The manoeuvres are defined in terms of a trajectory in three dimensional space together with an additional constraint - usually on the side slip angle - which completes the information needed for uniquely defining the control actions for the manoeuvre. The technique is well established and its capability has been demonstrated in a number of performance and design investigations (e.g. Refs.13,14). Underpinning the inverse simulation algorithm is a flight dynamics helicopter model, HGS (Ref. 15), of adequate authenticity for flight dynamics studies. The main features of the HGS formulation include a multi-blade description of main rotor flapping, dynamic inflow, an engine model and look-up tables for fuselage aerodynamic forces and moments; it is equivalent in structure and detail to the DERA real time simulation model used in the study.

In the ADS-33 evaluation methodology, MTEs are specified in terms of flight path and control strategy objectives, dynamic performance and task precision requirements. The latter are stated in terms of 'desired' and 'adequate' task performance standards in relation to track, height, heading and speed errors. The values set are representative of the performance levels expected to be achieved in real missions, whilst respecting aircraft flight envelope limits, e.g. gearbox torque, normal 'g', rotor rpm, control margins etc. The aim is to achieve a similar representation for the inverse simulation solution. The growing database of defined manoeuvres incorporated within HELINV contains a suite of MTEs taken from ADS-33 including the following:

Hover & low speed	Lateral Side-step, Acceleration-Deceleration, Bob-up/down, Hover turn
Forward flight	Roll axis slalom, Acceleration-Deceleration, Pop-up/Pop-down

These cases represent typical manoeuvres for an armed attack helicopter; more generally, for the purpose of developing the methodology, they also provide representative manoeuvre demands for all four primary control axes. To date the emphasis of the research has been on the battlefield mission where benefits of improved flight control are likely to be gained in the form of increased agility. Other cases, such as helicopter deck operations in the maritime role, are being addressed in related DERA programmes employing the same methodology. The description of the DERA slalom, one of the principal manoeuvres featured in the current investigation, is developed in section 4.1.

3.4 Control workload ratings:

In an important initial investigation, it was established (Ref. 8) that a typical transient manoeuvring task comprises two key piloting components, guidance and stabilisation, and that increasing task aggression can result in conflict between the two, resulting in a significant rise in workload. A key aim was to develop a control strategy analysis technique that could differentiate and extract the contributions of these two components. Preliminary results from analysis of trials data using adaptive wavelets demonstrated how individual wavelet transform components of records of pilot control activity can actually be associated with guidance and stabilisation elements of pilot control strategy (Ref 3). Furthermore, it was also shown that the concept could be applied to quantify changes in pilot control activity associated either with increasing task demand, or with modifications to the vehicle handling characteristics. Subsequently, results from analysis of experimental data have been used to develop and specify a set of rules for application to the wavelet data to determine control workload ratings; this process is described in more detail in sections 4.2 - 4.4 below.

3.5 Rule induction:

Experience with the rule induction technique in successfully modelling pilot ratings for complex flying tasks, via decision trees (Ref 16), indicates its potential value in translating workload metrics into workload ratings. The value of the approach lies in its objective treatment of subjective test data and in the accessible form of the induced rules. In the current application, and related to the discussion below, the input variables are the workload metrics derived from the adaptive wavelet analysis of the control responses and the response variable is the workload rating assigned by the pilot.

Rule induction, used in classification mode, approximates relationships of the form

$$class=f(x_1,\ldots,x_n)$$

where the $x_1,\ldots,x_n$ are input variables and *class* is the response variable, by a decision tree consisting of rules of the form:

IF *condition* THEN *action*.

In this rule, the *condition* involves the input variables $x_1,\ldots,x_n$ and the *action* is the designation of the given combination of input variables to membership of a particular class. The rules are determined solely from data-sets of samples of the form:

$$[\, x_1,\ldots,x_n, class].$$

by automated criteria for determining optimal splits at decision tree nodes. The Classification and Regression Trees (CART) (Ref. 17) package constructs binary decision trees from a set of presented data and includes the facility for splitting the presented data into training and testing sets in order to obtain an optimal tree. Results from the method are discussed in more detail below in section 4.5.

3.6 Mission effectiveness criteria:

From a mission effectiveness standpoint, a fundamental premise for the research was that minimising the vehicle piloting workload will release effort for mission tasks with a corresponding benefit to mission effectiveness. To maximise effectiveness, the overriding concern is to ensure that good performance is achievable at low workload. The Cooper-Harper rating scale provides a measure of the pilot workload required to achieve a defined performance, and Ref. 5 presents a probabilistic analysis of HQR data as a basis for exploring the relationship between handling qualities and effectiveness. The basic notion is introduced that handling deficiencies increase the likelihood of pilot error and, hence, can lead to accidents, incidents or task failure. Effectiveness may then be expressed in terms of the probability of 'task success', 'task failure' or 'loss of control' which, in Cooper-Harper terms, equate respectively to desired or adequate performance attainment, inadequate performance, or loss of control. To quantify these probabilities, a further assumption is made that, for operations with a given aircraft in a given role, a population of notional HQRs can be defined, which will conform to a Gaussian normal distribution, see Fig 2.

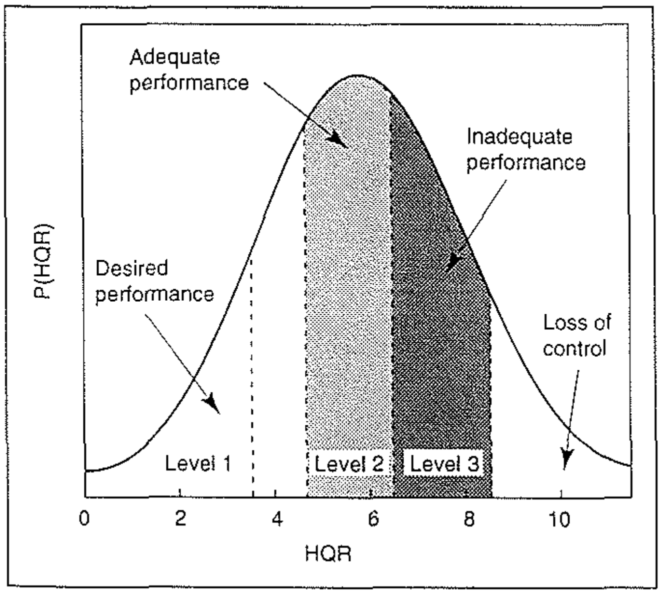

Fig 2. Notional distribution of HQRs

For a practical application of the concept, the acquisition of an appropriate data set presents a considerable problem. One simplified approach that has been explored is to use HQR data sets taken from piloted MTE evaluations. While such data do not span the full range of the general case, it is hypothesised that the sample would also be normally distributed and that the same probabilistic approach would serve as a basis for MTE effectiveness. An example of this type of application, using results taken from Lynx flight and simulation trials, is discussed in section 4.6 below. Ultimately, the aim is to a develop a similar application for predicted control workload ratings, proving the concept initially using MTE evaluation data. A further aim is to investigate the possibility of deriving a rating population for a complete mission evaluation, which would be achieved by applying MTE-based rating criteria to contiguous segments of control data from a flight sequence. Some progress has been made towards this goal using Lynx simulation data and these results are also discussed in section 4.7 below.

4 DEVELOPMENT ACTIVITIES

This section describes the development activity of each item of the overall methodology set out in section 3.2 as it has contributed to the overall programme.

4.1 Inverse simulation:

The application of inverse simulation requires attention to the authenticity of the underlying helicopter model and to the proper modelling of the relevant MTEs. For the present investigation, enhancements were made to HGS in the areas of AFCS modelling and various aerodynamic improvements relating to blade modelling.

Additional manoeuvres were added to the library of MTEs in HELINV to better represent those carried out by DERA in the simulated and flight trials. The DERA slalom is shown schematically in Fig. 3. It comprises three sections: in the first, the aircraft is displaced a fixed distance, h, laterally from the centre line and then its direction is reversed to displace the aircraft an equal distance on the opposite side of the centre line. The aircraft returns to the centre line and the second section is traversed along this in level flight. The third section is a mirror-image of the first, with the displacements interchanged. A smoothly connected piecewise polynomial representation is used for the lateral displacement and is defined as a function of time by the polynomial:

$$y(t) = \left[-\frac{1}{32}\left(\frac{t}{t_1}\right)^{13} - \frac{39}{64}\left(\frac{t}{t_1}\right)^{12} + \frac{83}{16}\left(\frac{t}{t_1}\right)^{11} - \frac{1617}{64}\left(\frac{t}{t_1}\right)^{11} + \frac{2475}{32}\left(\frac{t}{t_1}\right)^{9} - \frac{9801}{64}\left(\frac{t}{t_1}\right)^{8} - \frac{1539}{8}\left(\frac{t}{t_1}\right)^{7} - \frac{8991}{64}\left(\frac{t}{t_1}\right)^{6} + \frac{729}{16}\left(\frac{t}{t_1}\right)^{5} \right] h$$

for $0<t<3t_1$, that is for the first section, and similarly for the third; the displacement is zero for the mid section. The overall time for the manoeuvre is $tm=7t_1$ and the manoeuvre is flown at constant altitude and airspeed. The expression above for $y(t)$ possesses the required smoothness at its endpoints to blend with the track along the centreline without inducing spurious control activity. The use of polynomials to represent complex MTE trajectories may appear simplistic but previous research (Ref. 12) has validated this approach by demonstrating that the principal features of a manoeuvre may be adequately modelled provided sufficient smoothness constraints are imposed on the trajectory start and finish. A typical lateral cyclic stick response for a HELINV simulation of a Lynx carrying out the DERA slalom is shown in Fig. 4.

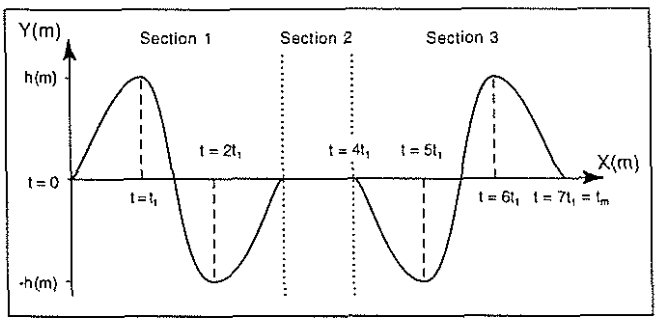

Fig 3. Schematic of DERA Slalom

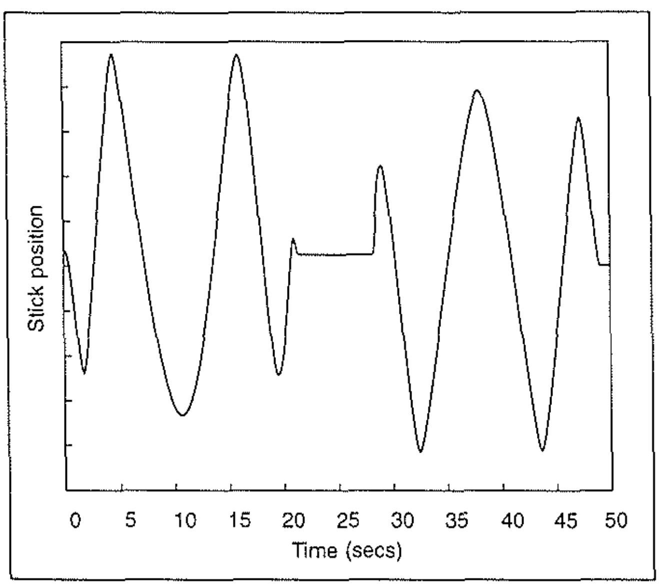

Fig 4. Lateral cyclic for Slalom MTE - HELINV Predictions

The concatenation of several mission task elements into a Multiple Manoeuvre Mission Sequence has also been implemented and is available for future work. It is described in detail in Ref. 18

The method provides representative manoeuvre demands for all four primary control axes. However, typical results from inverse simulation do not always contain the fine detail observed in piloted trials. Fig. 5 shows a typical control response from a piloted simulation and, while the key guidance actions can be correlated with those in Fig. 4, there are clearly differences in the detail. For this reason, until the simulation technology has advanced further, e.g. through developments in pilot modelling currently underway (Refs. 19, 20), the results from inverse simulation need to be interpreted with care and used to provide relative, rather than absolute, measures of workload.

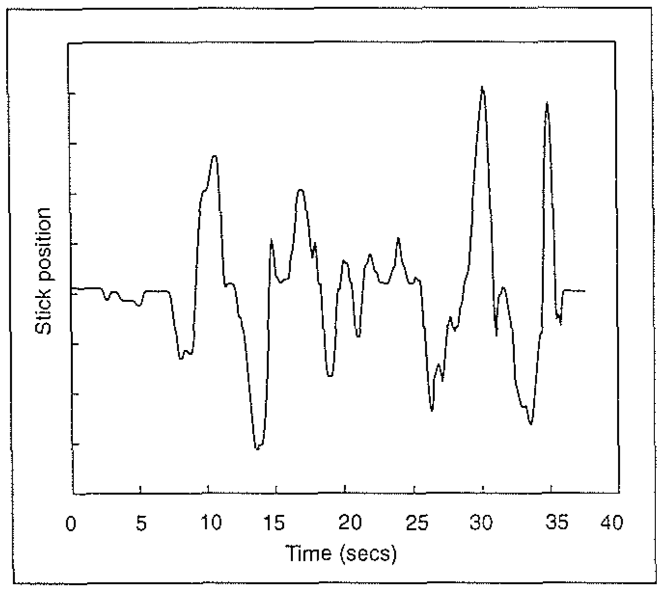

Fig 5. Lateral cyclic for Slalom MTE - Flight Measurements

4.2 Derivation of wavelet-based control attack charts:

In the initial stages of the research, a methodology was investigated in which wavelet analysis was used to identify components of workload from time-history records of pilot control activity (Ref 3). The method used to extract discrete components of pilot workload from records of control activity involves an initial transformation or 'whitening' of the signal - transforming the signal into a series of pulses. Adaptive wavelet decomposition (Refs 3, 4) is then performed on the whitened signal using pulse-shaped wavelets. The shape of the associated discrete component in the original record of control activity, or 'worklet', determines the whitening transformation employed. In a further development of the process, a whitening transformation with two free parameters has been evaluated, which can be tuned to achieve optimal reconstructions of control activity from the wavelet decomposition; this results in an alternative worklet profile in the form of a 'sharp-onset ramp with washout', Fig.6. Using this method of signal decomposition, control time histories are decomposed into a set of discrete transient events, each having a profile shape of the form illustrated in Fig 6. Associated with each such event, or 'worklet', there are three quantities: 'position' in the time history, scale Δt, related to ramp duration, and magnitude of control displacement Δz. As described in Ref 3, the decomposition data provides an 'attack chart' plot, Fig 7, in which each point corresponds to a discrete worklet. The plot axes are the associated control displacement and the 'attack parameter', where the latter is defined to be the inverse of wavelet scale t and has the dimension of 1/sec; the attack parameter is the control equivalent of the response quickness (Ref 2).

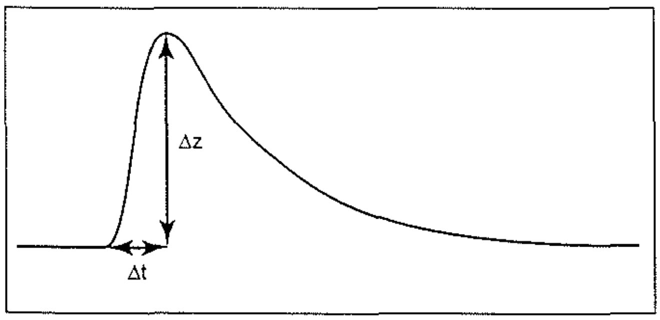

Fig 6. Analysing Wavelet - Transient Shaping Modules

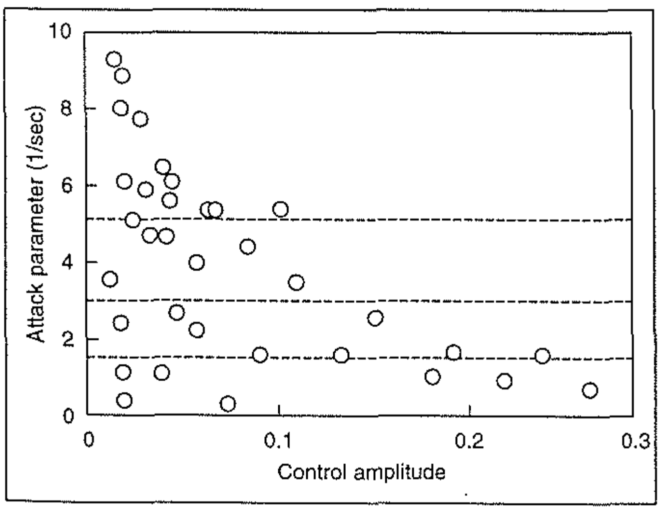

Fig 7. Control Attack Chart

4.3 Attack chart exceedance rate workload metrics:

Analysis of experimental data has shown that the exceedance rate (ER) for attack chart components distributed within specific bands of attack values correlate qualitatively with pilot ratings and opinion. A further refinement of the wavelet analysis application has also shown that it is possible to identify oscillatory components of control data, which may be attributed to over-control, or in the limiting case, to an actual pilot-induced-oscillation (PIO). The two processes, i.e. exceedance rate and oscillation detection, or what are referred to as ER and PIO analyses, have provided the basis for a set of rules for application to control time histories to determine control workload ratings. For ER analysis, the attack chart is partitioned into four predetermined ranges of attack parameters, which essentially represent key components of guidance or stabilisation related control inputs over four different frequency ranges (see Fig 7). The exceedance rates for discrete attack values within each range are then calculated from the associated data frequency distributions. Six significant exceedence rate-based 'features' have been identified, which summarise the magnitude and intensity of the control activity within each attack range. PIO analysis is carried out by application of a 'variable shape wavelet' (VSW) fitting process to the wavelet transformation of the original control displacement time history (Ref 21). The degree of 'over-control' represented by the VSW signal can be quantified in terms of an associated attack parameter value, the number of cycles in the sequence, and its 'relative energy' expressed as a proportion of the energy in the oscillation to the total energy contained within the transformed record.

4.4 Wavelet-based control workload ratings:

A set of rules and criteria have been defined for determining an overall workload rating, which comprise the sum of two contributions, from the ER and PIO analyses. Results from an application to Lynx flight data are shown in Fig 8, which shows a comparison of pilots' HQRs versus the predicted workload ratings for two different aircraft configurations, C2, corresponding to the aircraft without automatic flight control system (AFCS) engaged, and C3, with the AFCS engaged. The figure shows the mean, maximum and minimum pilot ratings for lateral side-step, slalom and acceleration-deceleration MTEs and the overall values for all MTEs. Mean, maximum and minimum predicted

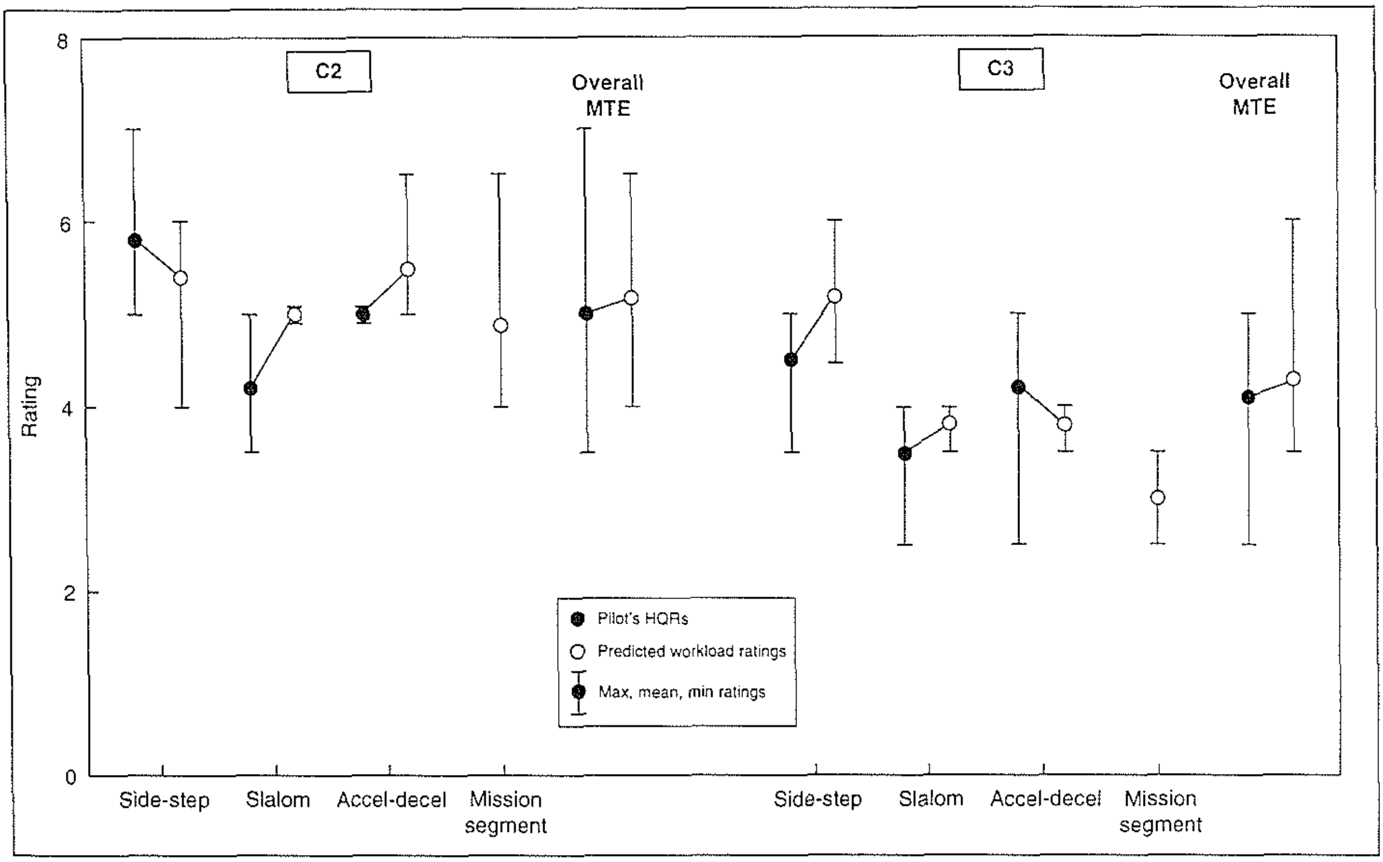

Fig 8. Predicted Control Workload Ratings Versus Pilot's HQRs

ratings for five selected segments from simulated continuous mission evaluations of the two configurations are also shown for comparison. The overall predicted mean ratings for both configurations were within less than 0.5 of a rating of the means of the awarded pilot ratings, i.e. 5.3 versus 5 and 4.3 versus 4.1 for C2 and C3 respectively. For the individual MTEs, the mean values were within 0.8 of a rating, the worst case being C2 in the Slalom, which was awarded a mean rating of 5.0 compared to a mean of 4.2 for the actual ratings. Both sets of results show good agreement in the overall trend of poorer ratings for C2 as compared to C3, which is consistent with the greater pilot compensation required when flying the unstabilised aircraft, C2. This is also reflected in the predicted ratings for the mission segment data, where C2 was awarded a mean rating of 4.9 as opposed to a rating of 3.0 for C3. Although these results are relatively limited, they do, nonetheless, provide a good illustration of the potential of the approach for future application in the methodology. They also support the original premise that the control attack chart captures the key piloting workload components of a given control strategy and is sensitive to pilot compensation for vehicle specific handling qualities deficiencies.

4.5 Attack chart rule induction workload metrics:

Rule induction techniques have been used to explore several different approaches to attack chart partitioning to predict the subjective workload ratings, on the basis of the number of events occurring in each chart region. Some examples of the types of chart partitions investigated are shown in Figure 9 where a typical partitioning divides the chart firstly in terms of attack (Fig 9a) and then both attack and amplitude (Fig 9b). The partioning form shown in Fig 9c is derived from equi-energy concepts and the response quickness boundaries (Ref 8). It is necessary, however, to give some consideration to the resulting number of partitions as each region constitutes a dimension in the input variable space for the rule induction process. If the partitioning of the chart is too refined then the training data, used to develop the rules, becomes sparse - leading to a tree with poor generalised predictive properties. From experiment (Ref 22) the most suitable partitions all separate the chart into horizontal bands using lines of constant attack, as shown in Figures 9(a) and 10(a). (Fig 10a shows partioning results derived from inverse simulation applied to piloted simulation data) The conclusion to be drawn is that the workload rating appears to be be

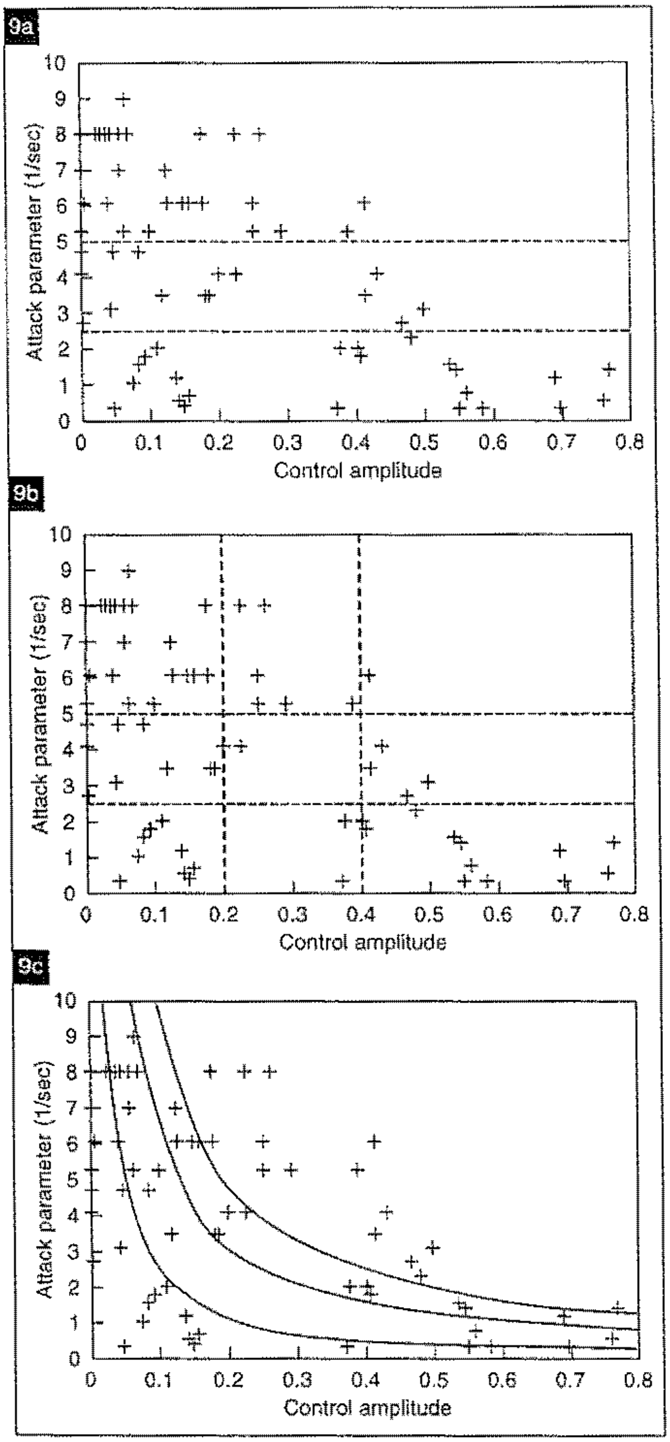

Fig 9. Partitioned Attack Charts Piloted simulation Data; Lynx Flying Slalom

relatively insensitive to the amplitude distribution of the discrete pilot control actions, at least as they appear on the attack chart, possibly indicating that the distribution of events is independent of their number.

The form of the most suitable chart partitioning was, in fact, derived independently of the exceedance work described in the previous section and, although the values of the attack used to divide the chart are not identical, the qualitative agreement between the two

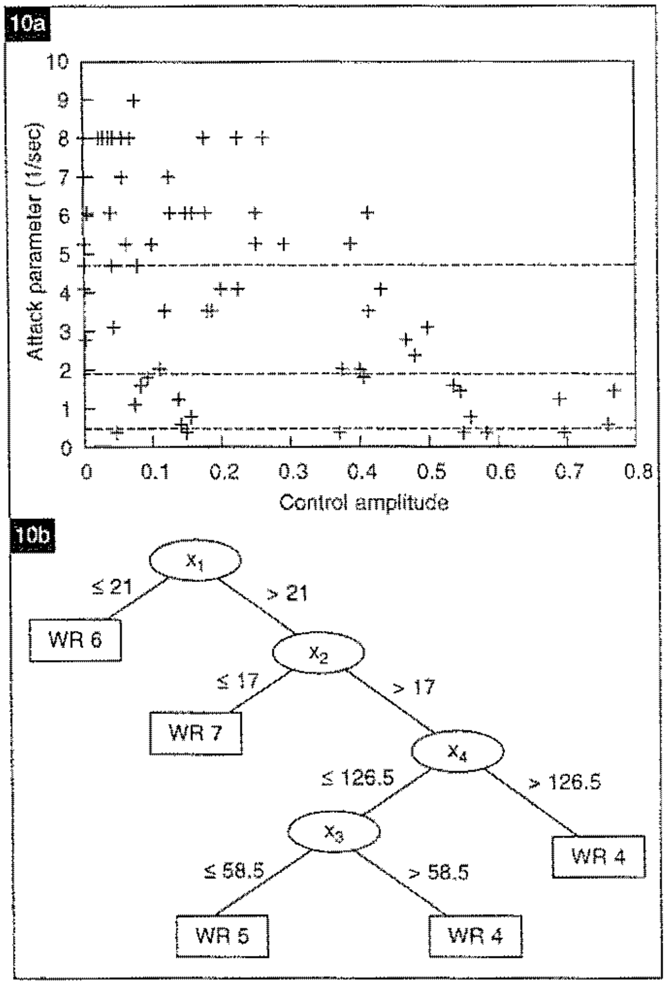

Fig 10. a) Attack Chart (HELINV Generated Partitions for Fig. 9 Data) b) Decision Tree

approaches is very encouraging. Prediction rules were derived using (training) data from trials on the DERA Advanced Flight Simulator (Refs. 9, 11); manoeuvres included the slalom, lateral sidestep, bob-up/down and accel-decel. As discussed in section 3.5, the frequency of attack values in each partition of the chart is recorded and, along with the corresponding workload rating, is used as input to CART to construct a binary decision tree. Figure 10(b) shows a typical decision tree generated from control responses in the slalom task. Note that here the variable xj corresponds to the j-th region of the chart and records the number of events, or worklets, located in that particular region. At each node in the decision tree, a split is performed on a single variable - sending cases left or right depending on the numerical value of the variable. The splitting procedure continues until each terminal node, represented by a rectangle, either contains N≤Nmin cases belonging to the same class. In order to predict workload ratings, unseen cases from a further AFS trial (Ref. 10) are then run down this tree until a terminal node is encountered and the particular case is allocated the rating associated with this node.

Table 1 shows the percentage of correct workload rating predictions obtained for those rules when they were applied to an independent set of data gathered during the Ref 10 trial for a similar set of manoeuvres. It can be seen that over 75% of the ratings were predicted correctly to within +/-1 workload rating - a level which is encouraging when compared with work in other applications. The correlation between the actual and predicted ratings has been found to be significant, at the 10% level, using Kendall's tau statistic. When it is acknowledged that these predictions are made solely on the basis of the detailed structure of the primary axis control response, the level of predictive accuracy is reassuring.

MTE	% correct predictions based on new data	% correct predictions based on new data ±1WR
Side-step	55.56	72.72
Slalom	50.00	75.57
Bob up-down	40.00	73.33
Accel/decel	33.33	77.78
Total	40.00	75.38

Table 1. Workload Rating Predictions

4.6 HQR probabilities and mission effectiveness criteria:

In an initial investigation of the HQR probability concept, data sets from an AFS simulation trial were used to derive probabilities of achieving desired, adequate or inadequate performance levels, or loss of control (Ref 23). Results for three different model configurations were compared and it was hypothesised that the probability data could serve as source of mission effectiveness criteria, both in relation to the predicted probability of success or failure in accomplishing an MTE and attrition rates due to loss of control. Subsequently, results from other trials have been used to derive preliminary effectiveness criteria, as summarised in Tables 2 and 3 and Fig 11. The specific example shown here represents the aggregated HQR results from in-flight evaluation of a set of low speed MTEs, which included a side-step, acceleration-deceleration, hover turn, bob-up/down manoeuvres, and which were evaluated at low, moderate and high levels of task aggression (Ref 11). The aircraft was evaluated both with and without the AFCS engaged. Table 2 shows mean (x_{HQR}) and standard deviation (s_{HQR}) and associated normal probabilities of achieving desired (Pr{HQR < 4.5}), adequate (Pr{4.5<HQR<6.5}) or inadequate (Pr{6.5< HQR<9.5}) performance standards, or loss of control (Pr{HQR>9.5}). Before computing the probabilities, the HQR sample data were subjected to a Chi-square 'goodness of fit' test, which confirmed the hypothesis that they conformed to an $N(x_{HQR}, s_{HQR}^2)$ distribution.

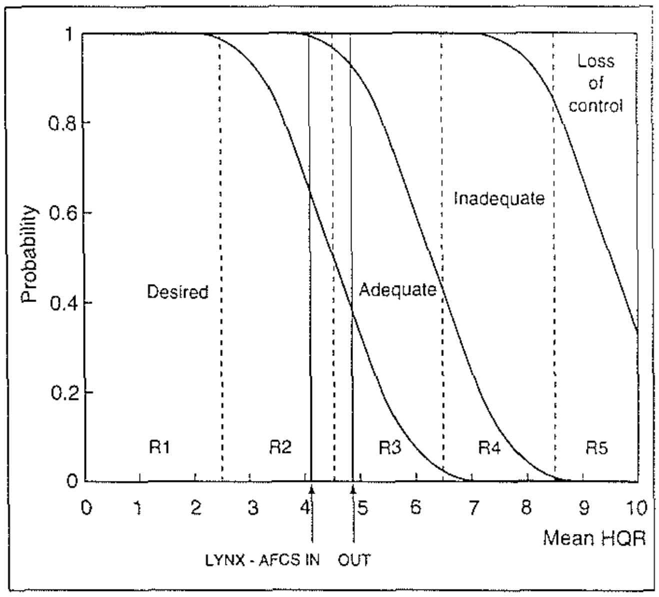

Fig 11. Statistical Effectiveness Criteria and Results for Lynx in Flight

AFCS in/out	N	x_{HQR}	s_{HQR}	Pr (n_1<HQR<n_2) given $N(x_{HQR}, s_{HQR}^2)$			
				n_2 = 4.5	n_1 = 4.5, n_2 = 6.5	n_1 = 6.5, n_2 = 9.5	n_1 = 9.5
IN	75	4.120	1.043	0.644	0.345	1.1×10^{-2}	1.2×10^{-7}
OUT	67	4.761	1.057	0.404	0.547	5.0×10^{-2}	3.6×10^{-5}

Table 2. Normal Probability Data for HQRs taken from Lynx Trials

4.7 Mission effectiveness criteria:

Cumulative Normal probability data for $N(x_{HQR}, 1)$ cases are shown in Fig 11, and used to illustrate the concept of a sample mean HQR-based set of MTE effectiveness criteria. The curves represent the probability bounds for desired, adequate and inadequate MTE performance and loss of control as a function of mean HQR. The dashed lines represent the demarcation of five proposed regions for MTE effectiveness criteria. A summary of the criteria is given in Table 3, which shows the range of mean HQR, associated probabilities and mission effectiveness attributes for each region. For comparison, the solid lines on Fig. 11 show how the Lynx flight data align with the criteria, where the augmented aircraft falls into effectiveness region 2 and unaugmented, into region 3; stability augmentation increases the chance of achieving the desired performance standards from 45% to 65%. This might be expected as, the Lynx's handling qualities are in accordance with the basic rate stabilisation properties of its AFCS; in a mission context, a moderate degree of pilot compensation is required to maintain flight envelope limits and, unaugmented, continuous pilot compensation is required to stabilise attitude and flight path. To exhibit region 1 effectiveness, at the very least additional AFCS mission functions would be needed, say to give height, position and speed hold capabilities. Beyond this, a high authority active control system could provide the capability for a carefree handling system for preservation of flight envelope limits, and tailoring handling qualities to specific mission requirements.

Effectiveness region	HQR Probabilities $N(x_{HQR}, s_{HQR}^2)$		Mission effectiveness attributes
	Mean	Max/Min*	
1	x < 2.5	P{D} = 97.75 P{A} = 2.25 P{I} = 0.00 P{L} = 0.00	• Minimal workload • Handling qualities are a positive attribute to mission effectiveness
2	2.5 < x < 4.5	P{D} = 50.20 P{A} = 47.55 P{I} = 2.25 P{L} = 0.00	• Moderate workload • Handling qualities deficiencies will not significantly degrade mission effectiveness
3	4.5 < x < 6.5	P{D} = 2.30 P{A} = 47.90 P{I} = 49.68 P{L} = 0.13	• Considerable-extensive workload • Handling qualities deficiencies will degrade mission effectiveness
4	6.5 < x < 8.5	P{D} = 0.00 P{A} = 2.30 P{I} = 81.95 P{L} = 15.74	• Maximum tolerable workload • Handling qualities deficiencies will significantly degrade mission effectiveness
5	x > 8.5	P{D} < 0.00 P{A} < 2.30 P{I} < 81.95 P{L} > 15.74	• Intense workload • Loss of control is likely at some stage in the mission

* D = Desired A = Adequate I = Inadequate L = Loss of control

Table 3. MTE Effectiveness Criteria assuming a given x_{HQR} and $s_{HQR}^2 = 1$

5 FUTURE DEVELOPMENTS

Anticipated future developments are associated with reinforcing the robustness and predictive authority of the several components of the methodology. The foundation for the whole exercise is the ability to simulate manoeuvres and to generate authentic control responses. A shortcoming of the current approach is that responses and control activity do not feature all of the detail found in data from piloted trials, with less-than-perfect pilots. One approach, currently being examined, incorporates a pilot model within the algorithm and to allow a controlled trade off between flight path precision and control activity. Although attractive from the point of view of potential added realism, moving away from the perfect, towards an imperfect, pilot carries with it increased complexity and the rejection of one main benefit of inverse simulation which is the absence of any parameters that need to be tuned or identified in a wider validation activity. However, there are clearly significant benefits to balance the disadvantages, including the ability to model flight envelope limits, control limits and actuator saturation as well as the influence of piloting errors on performance and flight safety.

It is clear that the measure of independently obtained agreement between the exceedance and rule induction, based interpretation of the control attack chart, indicates an underlying principle and a consolidation of the two approaches is called for. This would involve agreeing on the optimal wavelet shape and on the most significant partitioning of the attack chart. Statistical validation of the results of any predictive model is a necessity.

The analysis of the primary control axis alone is an acknowledged limitation of the reported application of the methodology and a wider correlation with the responses of all axes have been tentatively explored without, to date, firm conclusions. Clearly, the effect of off-axis co-ordination and anticipation is an area that demands careful analysis at an early opportunity

One advantage of the rule induction approach is that additional data is easily incorporated in order to update and refine the rule base. Future flight and simulation test programmes should be designed to begin to accumulate a more authoritative database.

A consequence of all of the rules being produced by this research is that, even though they may be accepted as a coarse generalisation, it is possible to reverse the inductive process and ask whether pilots are correctly awarding ratings when compared to a validated methodology. There is, it would appear, scope for using the rules to train pilots to give a consistent and accurate rating in appropriate circumstances.

6 CONCLUSIONS AND RECOMMENDATIONS

An overview of a new methodology for predicting pilot workload and the impact on mission effectiveness has been presented. The overall methodology relies on a co-ordination and integration of several substantial individual research activities including inverse simulation, wavelet-based control analysis, exceedance/rule-based prediction and probabilistic handling qualities. Sufficient progress has been made with each of the individual aspects and their integration to assert confidently the feasibility of predicting workload ratings and metrics of practical value at the design stage using aircraft configurational information. The following observations and conclusions are drawn:

i. The pilot rating based on introspection of control strategy, compensation and performance is an important fundamental component in the development of the current methodology. When awarded for the primary control axis of a task, it is assumed to be an accurate indicator of the dominant pilot workload in flight and simulation tests.

ii. Inverse simulation provides an efficient off-line approach to estimating the control requirements to fly different mission task elements.

iii. Wavelet-based control analysis leading to the estimation of worklets and presentation on a control attack chart provides an effective method for deriving workload components (e.g. stabilisation and guidance).

iv. Control workload ratings may be derived from the attack charts in a reliable and reproducible manner using the exceedance and rule-based approaches described in this paper.

v. Control workload metrics allow the mission effectiveness of rotorcraft to be quantified in terms of probability of mission success/failure or loss of control; such predictions can prove invaluable at an early stage in the design process.

The capability of the integrated process will be enhanced by studies to:

i Increase the authenticity of the control strategy generated by rotorcraft inverse simulation via realistic pilot models.

ii Further calibrate the accuracy and consistency of workload prediction.

iii Address other contributory factors to pilot workload, including multiple axis control strategies.

All of these aspects are being addressed by current research in the collaborating institutions.

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