Rotorcraft Flying Qualities Improvement Using Advanced Control

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ABSTRACT

We report on recent experience gained when a multivariable helicopter flight control law was tested on the Large Motion Simulator (LMS) at DRA Bedford. This was part of a study into the application of multivariable control theory to the design of full-authority flight control systems for high-performance helicopters. In this paper, we present some of the results that were obtained during the piloted simulation trial and from subsequent off-line simulation and analysis. The performance provided by the control law led to level 1 handling quality ratings for almost all of the mission task elements assessed, both during the real-time and off-line analysis.

INTRODUCTION

The continuing drive to extend the operational capabilities of combat helicopters is demanding advanced flight control systems with handling qualities tailored appropriately for the mission task. By reducing pilot workload and allowing full use of the whole performance envelope, there is significant potential for improved mission effectiveness and survivability, particularly when required to manoeuvre at low level in bad weather and/or at night.

Leicester University has for the past three years been working on a research contract funded by the Defence Research Agency (DRA) Bedford, the primary aim of which has been to investigate the role of advanced multivariable frequency domain control theory to the design of helicopter flight control laws. The multivariable frequency domain approach is seen as essential if satisfactory decoupled performance is to be maintained in the presence of uncertain high frequency dynamics and disturbances. Here we report on the piloted simulation and off-line assessment of a controller designed by the first two authors under the terms of that agreement. The main purpose of the agreement was to enable an in-depth computer simulation study, backed up by periods of piloted simulation, that would help to assess further the role that advanced control theory might play in improving the handling qualities of future military helicopters. Our latest work follows on from earlier collaboration dating back to the mid 1980's between DRA Bedford and the second author [1,2,3], perhaps the most notable achievement of which was the piloted helicopter simulation of a multivariable control system designed using H-infinity optimal control theory [3].

The main achievement of the last three years work has been the significant improvements that have been obtained in relation to earlier

results [3,4], particularly during the last twelve months, in terms of wide-envelope decoupled performance, robust stability and compliance with ADS-33C [5]. This paper focuses on some of these latest results.

Description of the mathematical model

The mathematical model of the Lynx used for this study was the DRA Bedford Rationalised Helicopter Model (RHM) [6] which was used for both analysis and piloted simulation. The RHM models the separate aerodynamic force and moment contributions of the main rotor, tail rotor, fuselage, fin and horizontal stabilizer with the main rotor model consisting of rigid constant chord blades hinged with stiffness in flap at the centre of rotation. A constant lift slope and uniform induced flow are assumed and unsteady aerodynamic effects are ignored. A third order engine model defines torque and rotor speed degrees of freedom. Correlation with flight data is, in general, satisfactory and qualitative pilot comment has been favourable. Research is continuing to further improve the modelling fidelity of the rotor dynamics.

The same model was used for real-time piloted simulation and off-line handling qualities assessment.

Robustness

The equations governing the motion of the helicopter are complex and impossible to formulate with absolute precision. Consequently any mathematical model used for control synthesis will inevitably be inaccurate to some degree. Robustness means in essence the insensitivity of a feedback system to model error, parameter variations and non-linearities. Robust control theory provides methods of designing controllers that are insensitive to the errors and approximations present in the models that are available to the designer. Numerous design methods have been proposed over the last three decades which can to varying degrees accommodate robustness constraints. Here, a method based on H-infinity optimization was used.

The starting point for our designs was a set of five eighth-order linear differential equations modelling the small-perturbation rigid body motion of the aircraft about five trimmed conditions of straight-and-level flight in the range 0 to 80 knots. The controller designs were first evaluated on the eighth-order models used in the design, then on twenty-one state linear models, and finally using the full nonlinear model. The robust design methodology used in the controller design did turn out to provide excellent robustness with respect to non-linearities and time delays simulated although not explicitly included in the linear design process.

OBJECTIVES AND DESIGN METHOD

The main design objectives were:

• Robust stabilization of the aircraft with respect to changes in flight condition, and model uncertainty and non-linearity.

• High levels of decoupling between primary controlled variables.

• Compliance with the ADS-33C Level 1 criteria.

Design method

The method that was used to synthesize the control law was based on the H-infinity open loop methods that have been widely documented recently [7]. It is not intended to discuss the design techniques in detail here, but it is worth noting that the procedure adopted led to a two degree-of-freedom multivariable controller that robustly stabilized the aircraft over a wide range of flight conditions, whilst simultaneously

forcing the closed loop system to approximate the behaviour of a specified transfer function model. It has also been found that the ADS-33C bandwidth requirements impact directly on the cross-over frequency of the loop shape weighting functions used in the design process. The overall control law was actually comprised of five controllers, designed at a range of flight conditions between 0 and 80 knots, each one having a Kalman filter-like structure. As the dynamics of the open-loop aircraft vary with speed, so too did the controllers obtained at each operating point. Therefore, these controllers could be scheduled with forward speed if required, to give wide-envelope performance.

Response type

The basic aim of the design was to synthesize a full-authority controller that robustly stabilized the aircraft and provided a decoupled Attitude-Command/Attitude Hold (ACAH) response type that closely approximated the behaviour of a simple transfer-function model.

The outputs to be directly controlled were:
- Heave velocity
- Pitch attitude
- Roll attitude
- Heading rate

With a full authority control law such as that proposed here, the controller has total control over the blade angles, and is interposed between the pilot and the actuation system. The pilot flies the aircraft by issuing appropriate demands to the controller. These demands, together with the sensor feedback signals, are fed to the flight control computer which generates appropriate blade angle demands. Other than that we make no assumptions about the implementational details.

The controller was designed to operate on six feedback measurements: the four controlled outputs listed above and the body-axis pitch and roll rate signals. The other inputs to the controller consisted of the 4 pilot inceptor inputs.

The control law output consisted of four blade-angle demands:
- Main rotor collective
- Longitudinal cyclic
- Lateral cyclic
- Tail rotor collective

These demands were passed directly to the actuator model.

Controller scheduling

The controller was designed to run in either of two modes: (i) fixed gain, (ii) interpolated. In fixed gain mode, the closest controller for the given flight condition would be switched in and provide control. This controller would remain operative until the mode was de-selected. If the interpolated mode was engaged, the controllers would be interpolated smoothly as a function of airspeed to compensate for variation in dynamics. To implement for real would require an accurate measurement (or estimate) of forward airspeed.

Outer-loop modes

To enhance the handling qualities provided by the basic ACAH response of the inner loop H-Infinity controller, three outer loop modes were also implemented:

• Turn coordination: this was provided by augmenting the heading rate demand as a function of bank angle at moderate/high speed. This enabled a coordinated turn to be effected as a single axis task

• Automatic trimming: this was achieved using a trim-map to offset the linear inner loop controller with the appropriate trim attitude.

22:04:12   25-NOV-92   RHM15 Ø Knots
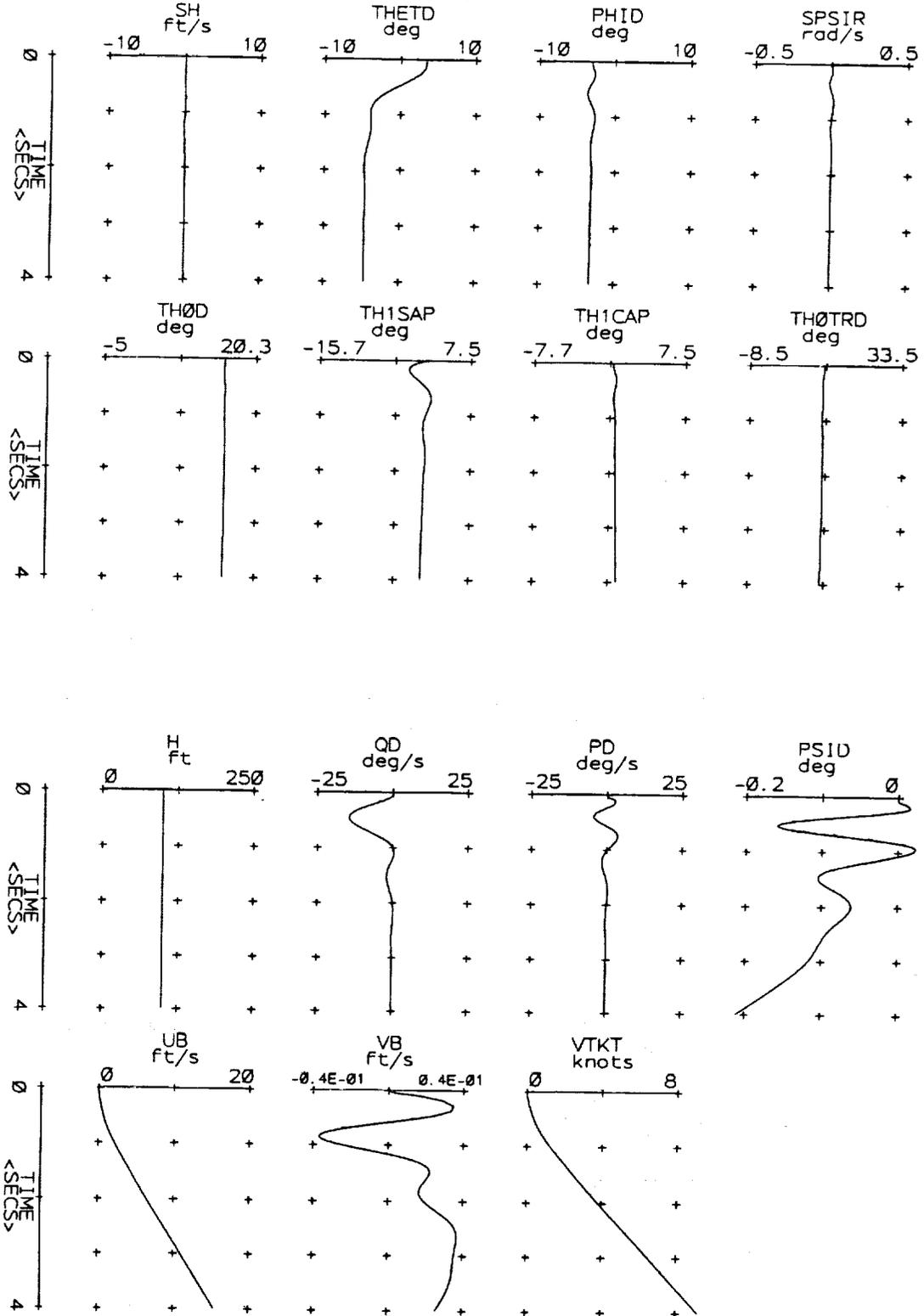
Figure 1 — Pitch axis step response
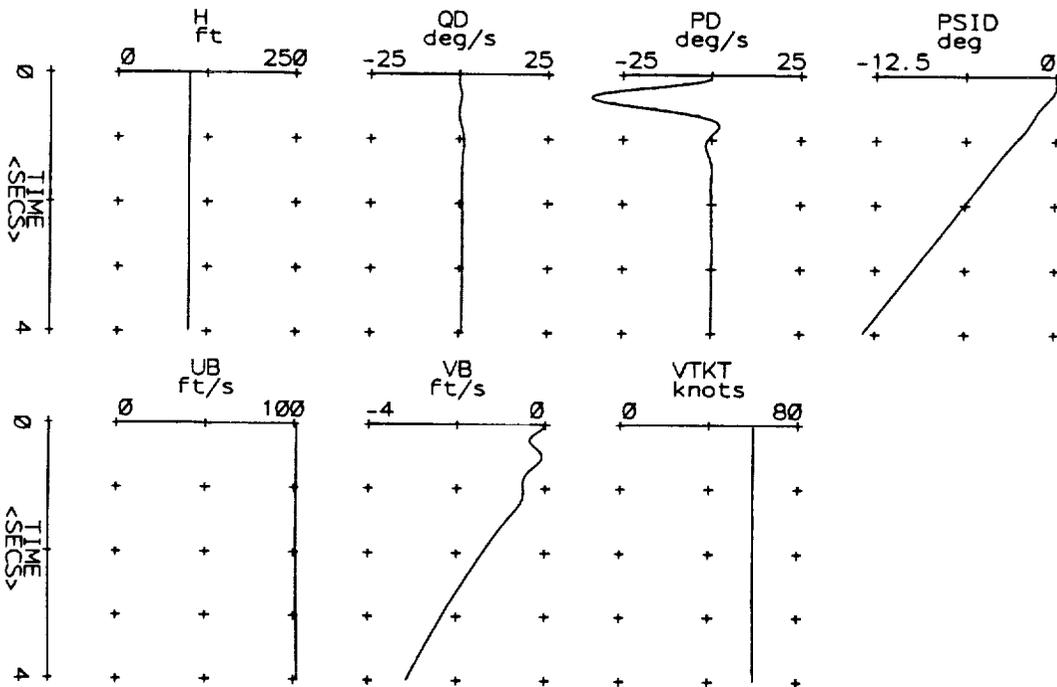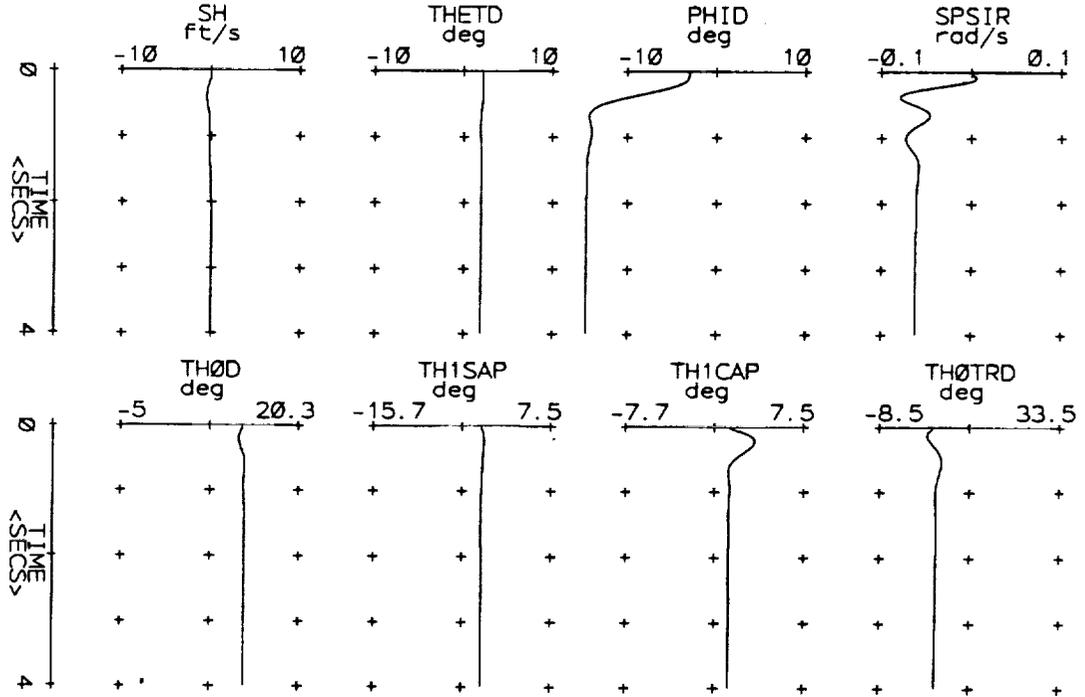
Figure 2 - Roll axis step response

• Hover acquisition/hold: this mode enabled the pilot to acquire and hold hover automatically. Longitudinal and lateral velocity state estimates were needed to achieve this.

During the piloted trials, the first two modes were used continuously, but insufficient time was available to evaluate the hover acquisition utility.

Step response analysis

The response of the closed loop system (comprising controller and full nonlinear model) to step input demands on pitch and roll channels are shown in Figures 1 and 2. These show, respectively, an acceleration from hover and the commencement of a co-ordinated turn at 60 knots. In both cases there is seen to be minimal cross-coupling.

HANDLING QUALITIES ANALYSES

Reference [5] details the latest requirements specification for combat helicopters which is intended to ensure that mission effectiveness will not be compromised by deficient handling qualities. The requirements are stated in terms of three limiting "levels" of acceptability of one or more given parameters. The levels indicate performance attributes that equate with pilot ratings on the Cooper-Harper scale. A MATLAB Handling Qualities Toolbox [8] was used as a supplement to existing computer aided control system design packages in order to integrate handling qualities assessment into the complete design and analysis cycle. The dynamics of the closed loop vehicle were assessed against the dynamic response requirements specified in sections 3.3 and 3.4 of [5] using the off-line simulation model. A selection of the results are reproduced here.

Short term response

The bandwidth (ω_{bw}) and phase delay (τ_p) parameters were calculated using frequency sweep inputs on pitch, roll and yaw axes to determine the frequency responses of the closed loop system. The values obtained at 0 and 50 knots are given below.

Table I - Bandwidth and phase delay (hover)

	ω_{bw} (rad/sec)	τ_p (sec)	Level
Pitch	4.88	0.1156	1
Roll	6.44	0.1211	1
Yaw	2.60	0.1002	2

Table II - Bandwidth and phase delay (50 knots)

	ω_{bw}	τ_p	Level
Pitch	4.93	0.1223	1
Roll	6.53	0.1220	1
Yaw	2.35	0.0936	2

These values are plotted for pitch and yaw axes in Figures 3 and 4, with the level 1, 2, and 3 boundaries superimposed. The high roll-axis bandwidth parameters fell outside the plotting range.

Mid-term response

To satisfy level 1 handling qualities criteria, a damping factor of at least 0.35 is required in pitch and roll axes. The following values were calculated by analysing the transient responses to pulse attitude demands in pitch and roll channels.

Combat/Target Track
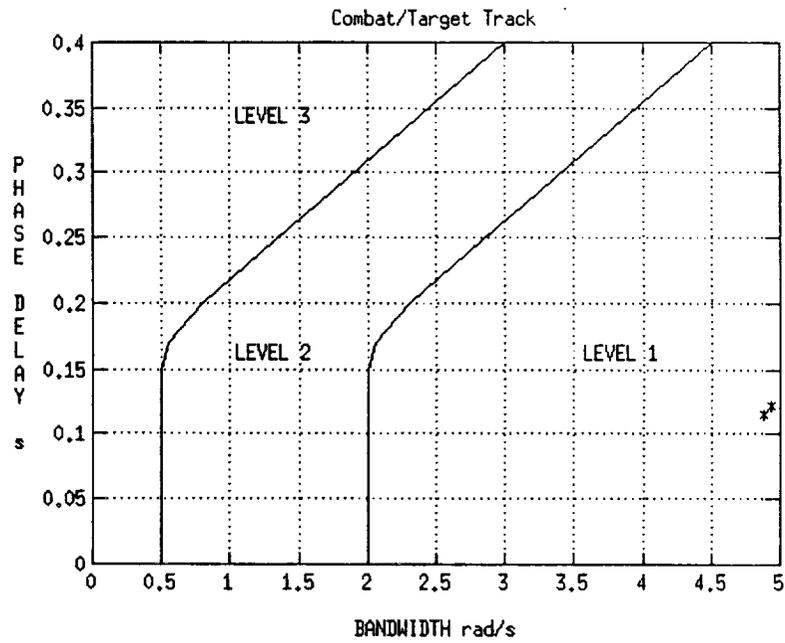
Figure 3 - Pitch axis short-term response

Combat/Target Track
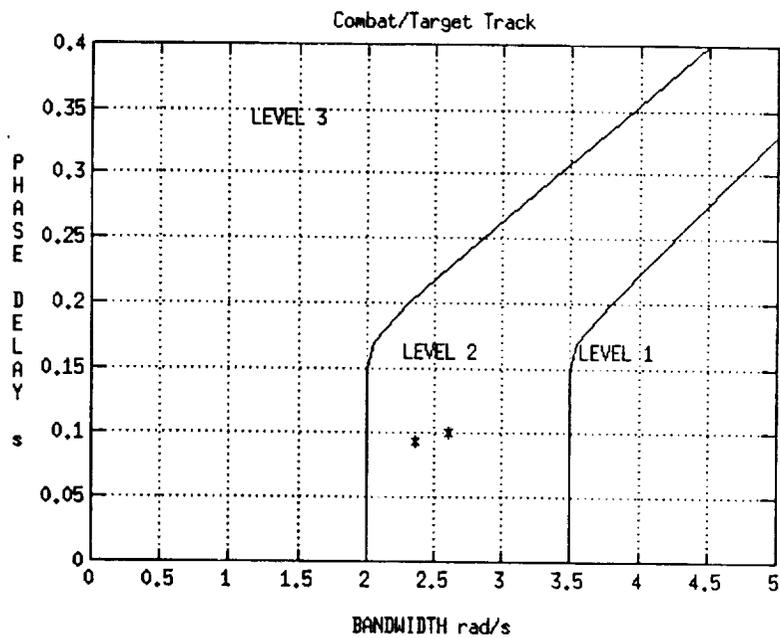
Figure 4 - Yaw axis short-term response

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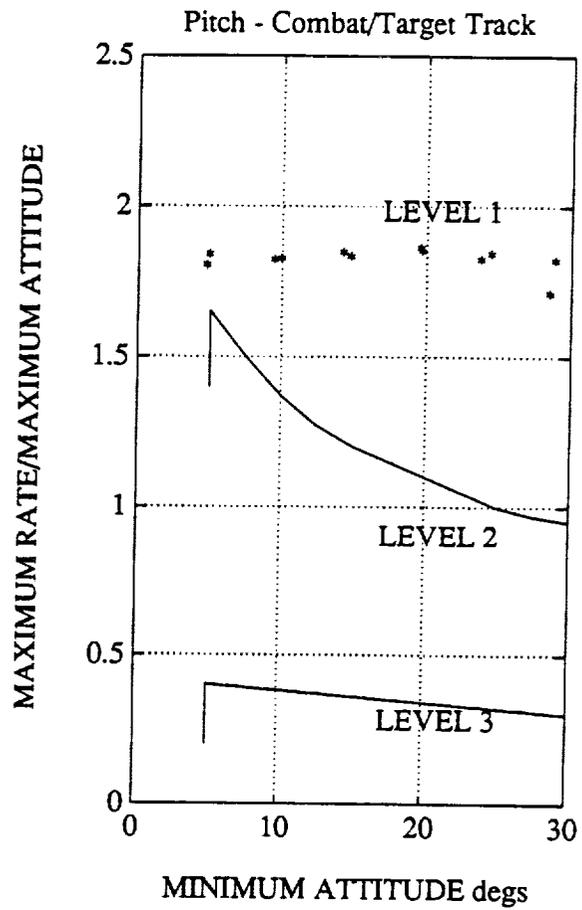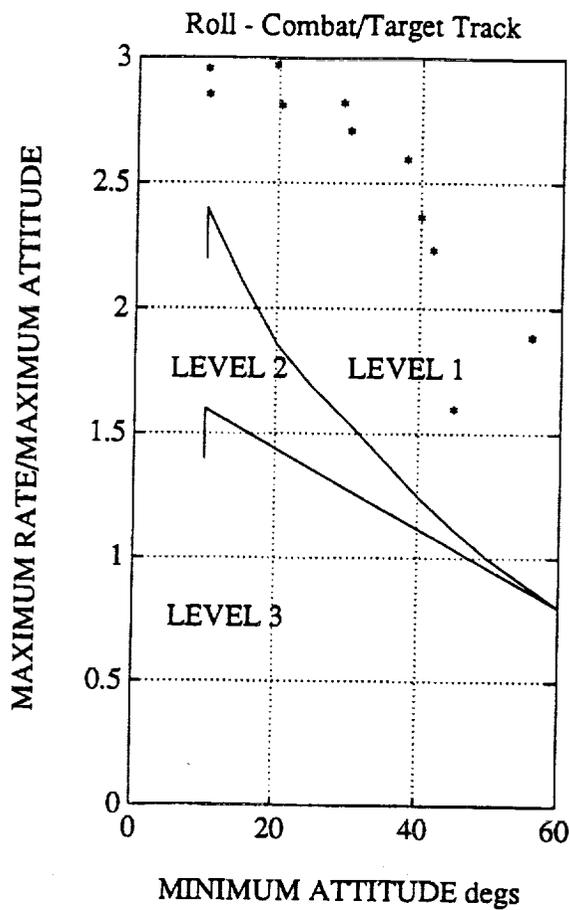
Figure 5 - Agility parameter (0 and 50 knots)

(Moderate amplitude response)

Table III - Damping Factor

	0 knots	50 knots
Pitch	0.75	0.81
Roll	0.94	0.98

These values comfortably satisfy level one requirements.

Moderate amplitude response

Using step inputs of varying sizes, compliance with the moderate amplitude criteria was assessed. Again, level 1 requirements were easily satisfied on pitch and roll axes. Figure 5 displays this information for both channels. The figure shows the agility parameter ($q_{max}/\Delta\theta$ versus $\Delta\theta$ and $p_{max}/\Delta\phi$ versus $\Delta\phi$) for a range of pitch and roll attitude changes at hover and 50 knots, with the boundaries which demarcate levels 1, 2 and 3 superimposed.

Inter-axis coupling

The ADS-33C level 1 requirement is that pitch-to-roll and roll-to-pitch coupling be less than 25%. The hover interaction levels are given in Tables IV and V.

Table IV - Pitch to roll coupling (Hover)

θmax	ϕmax	ϕmax/θmax (%)
9.99°	0.77°	7.9
19.74°	1.58°	8.1
31.24°	2.03°	6.9

Table V - Roll to pitch coupling (Hover)

θmax(deg)	ϕmax(deg)	θmax/ϕmax (%)
0.41°	10.07°	4.1
0.99°	20.32°	4.9
1.90°	30.48°	6.2

PILOTED SIMULATION ON THE DRA BEDFORD LARGE MOTION SIMULATOR

The simulation model was written in FORTRAN and run on an Encore Concept-32 computer with an integration step of 20 mS. A Lynx-like single seat cockpit was used, mounted on the AFS large motion system which provides ± 30 degrees of pitch, roll and yaw, ± 4 metres of sway and ± 5 metres of heave motion. Also, the pilot's seat was dynamically driven to give vibration and sustained normal acceleration cues. The visual display was generated by a Link-Miles IMAGE IV CGI system and gave approximately 48 degrees field of view (FOV) in pitch and 120 degrees FOV in azimuth with full daylight texturing. A three axis side-stick was used to control pitch, roll and yaw together with a conventional collective for heave.

Handling qualities were assessed for three hover/low speed mission task elements (sidestep, quick-hop, bob-up) and three moderate/high speed tasks (lateral jinking, hurdles, yaw pointing) using CGI databases developed by DRA [9] for the Euro-ACT programme [10]. The pitch and roll tasks were originally developed in flight trials and to maintain correspondingly representative control strategy, task aggression and task performance, the simulation visual databases are enhanced with additional artificial cues.

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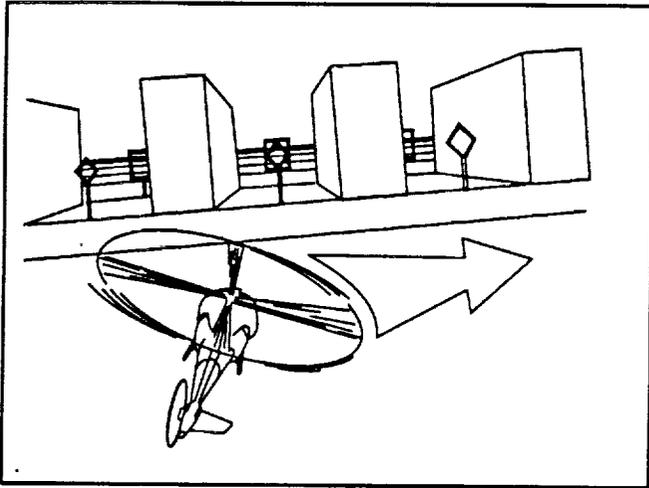
(a) Sidestep task
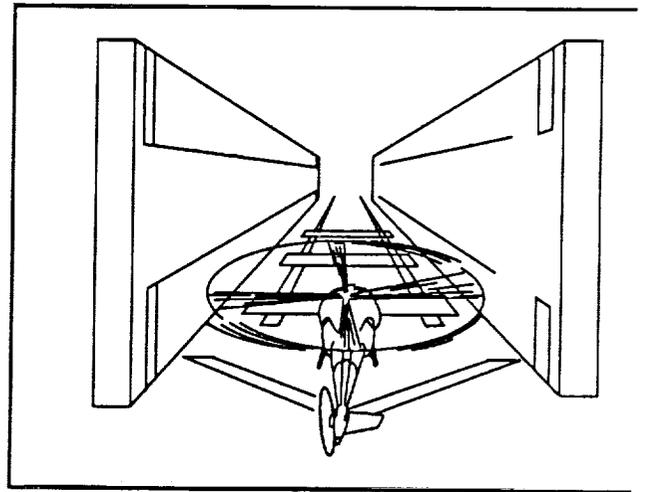
(b) Quick-hop task
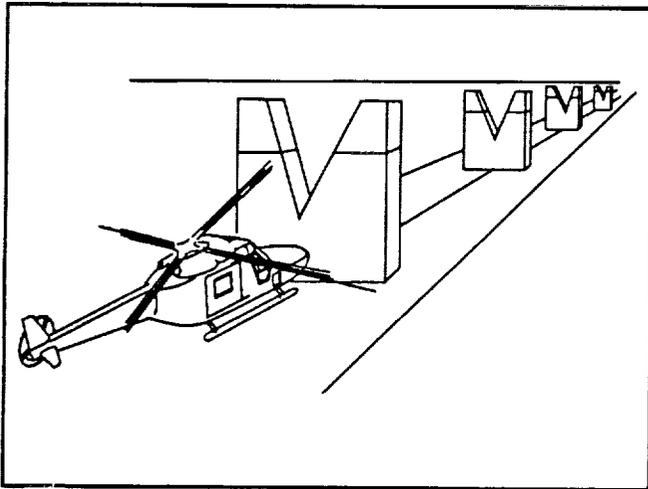
(c) Hurdles / Bob-up task
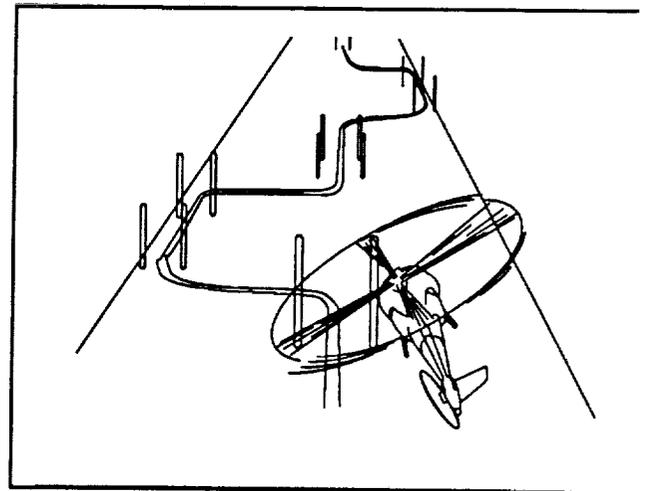
(d) Lateral jinking task

Figure 6

Two DRA test pilots took part in the trial, both with significant experience of Lynx and the AFS. For each task in turn, the pilot performed two or three familiarisation runs before performing a definitive evaluation run, at the end of which the simulation was paused so that comments and handling qualities ratings could be recorded.

Sidestep task description

With reference to Figure 6a, the objective was to translate sideways through 150' from a hover at a height of 30′ above ground level in front of one diamond and square sighting arrangement, to acquire and maintain a stable hover in front of the next sighting system. Maintaining any two of the diamond points within the square satisfied the desired ±10' lateral position and height tolerances. Task aggression was determined via initial bank angle, with 10°, 20° and 30° corresponding to low, moderate and high levels of aggression. Figure 7 shows a time history of one particular sidestep manoeuvre.

Quick-hop task description

The quick-hop task (Figure 6b) is the corresponding longitudinal task to the sidestep, requiring a re-position from hover over a distance of 500'. Again, similar levels of initial pitch attitude were used to determine the task aggression. The task was flown down a walled alley to give suitable height and lateral position cues and the terminal position tolerance was increased to ±30' to allow for the reduced FOV over the nose.

Bob-up task description

The bob-up task was performed in front of one of the V-notch hurdles (Figure 6c). From a hover aligned with the bottom of the V-notch, the pilot had to acquire and maintain a new height denoted by the bottom of the black tips. Task aggression was determined

subjectively by the pilot based on magnitude of collective displacement.

Lateral jinking task description

The lateral jinking task concerned a series of 'S' turns through slalom gates followed by a corresponding line tracking phase (Figure 6d). The task had to be flown whilst maintaining a speed of 60 knots and a height of 25' AGL. Once more, bank angle was used to determine task aggression with 15, 30 and 45 denoting low, moderate and high levels of aggression. Figure 8 shows the time history of one particular manoeuvre.

Hurdles task description

Using the same V-notch hurdles as seen for the bob-up task, a collective-only flight path re-positioning task was flown at 60, 75 and 90 knots to represent increasing task aggression. From an initial height aligned with the bottom of the V-notch, the pilot had to pass through each hurdle at the height denoted by the bottom of the black tips and then regain the original speed and height as quickly as possible.

Yaw pointing task description

Whilst translating down the runway centre line at 60 knots, the pilot was required to yaw to acquire and track one of a number of offset posts. Task aggression was determined by the magnitude of the initial offset.

Table VI is a compilation of one of the pilot's questionnaires.

Table VI - Pilot comment

Task	Level of aggression	Pilot comment	HQR	Level
Side-step	Low	Loads of spare capacity	2	1
	Moderate	Task workload still minimal, response perfect.	2	1
	High	Increased level of aggression does not increase workload. Very easy.	2 (low)	1
Quick-hop	Low	Desired performance easily achieved. Slight right drift. 3-axis task. A lot of model inertia. Control law good.	2	1
	Moderate	Easier at higher aggression because less anticipation required. No problems.	2	1
Hurdles	Low	Desired performance achieved satisfactorily. Yaw coupling only problem, but some spare capacity.	3	1
	High	At top of hurdle, control activity high and little spare capacity. > 10° coupling into heading.	5	2
Lateral jinking	Low	Stacks of spare capacity. Minimal control activity. Single axis task. No cross-coupling.	2	1
	Moderate	..	2	1
	High	..	3 (low)	1
Yaw pointing	V. low	Adequate performance achieved with difficulty. Control activity high. Not much spare capacity. Precision difficult.	5	2
	Low	PIO problems. Very high yaw inertia. Low sensitivity, possibly some lag. Maximum rate O.K. but needs to be tighter.	7	3
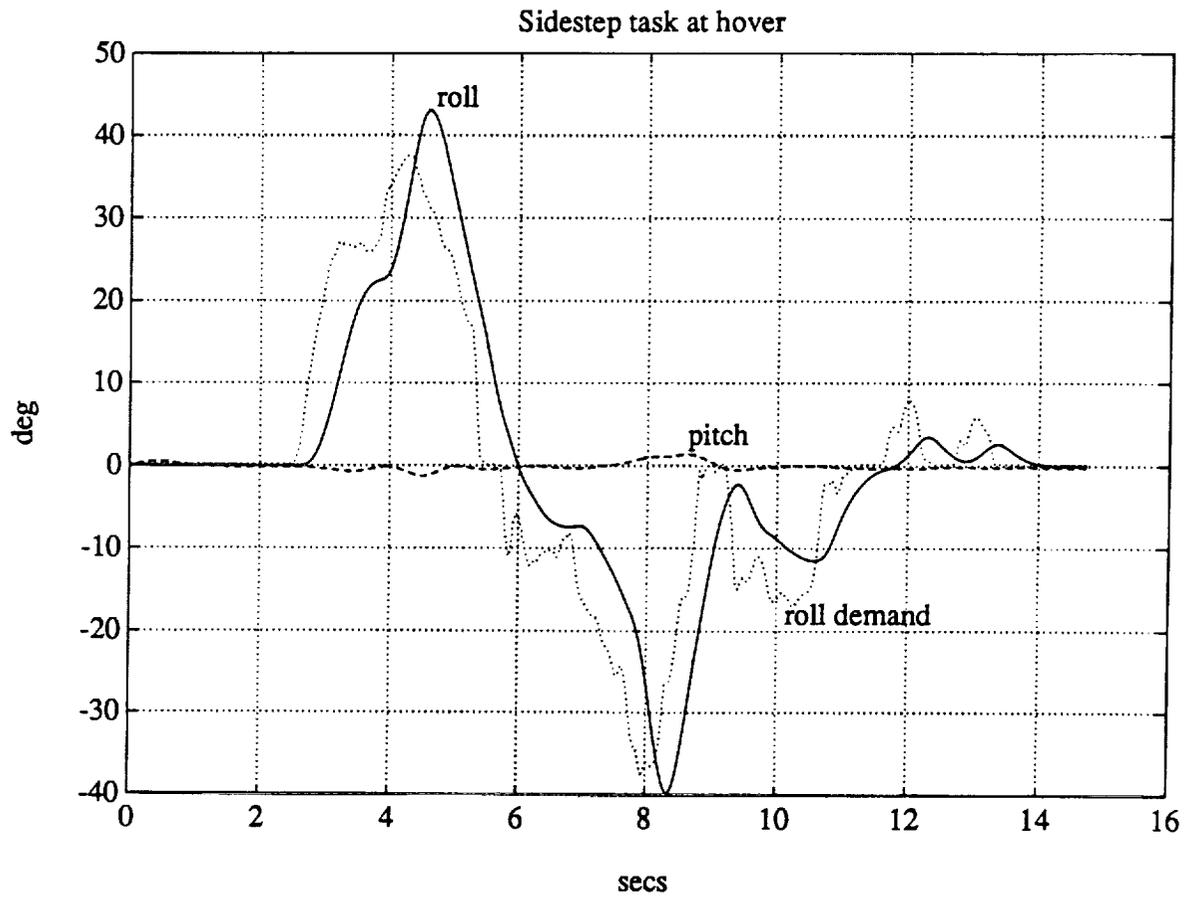
Figure 7 - Sidestep task data
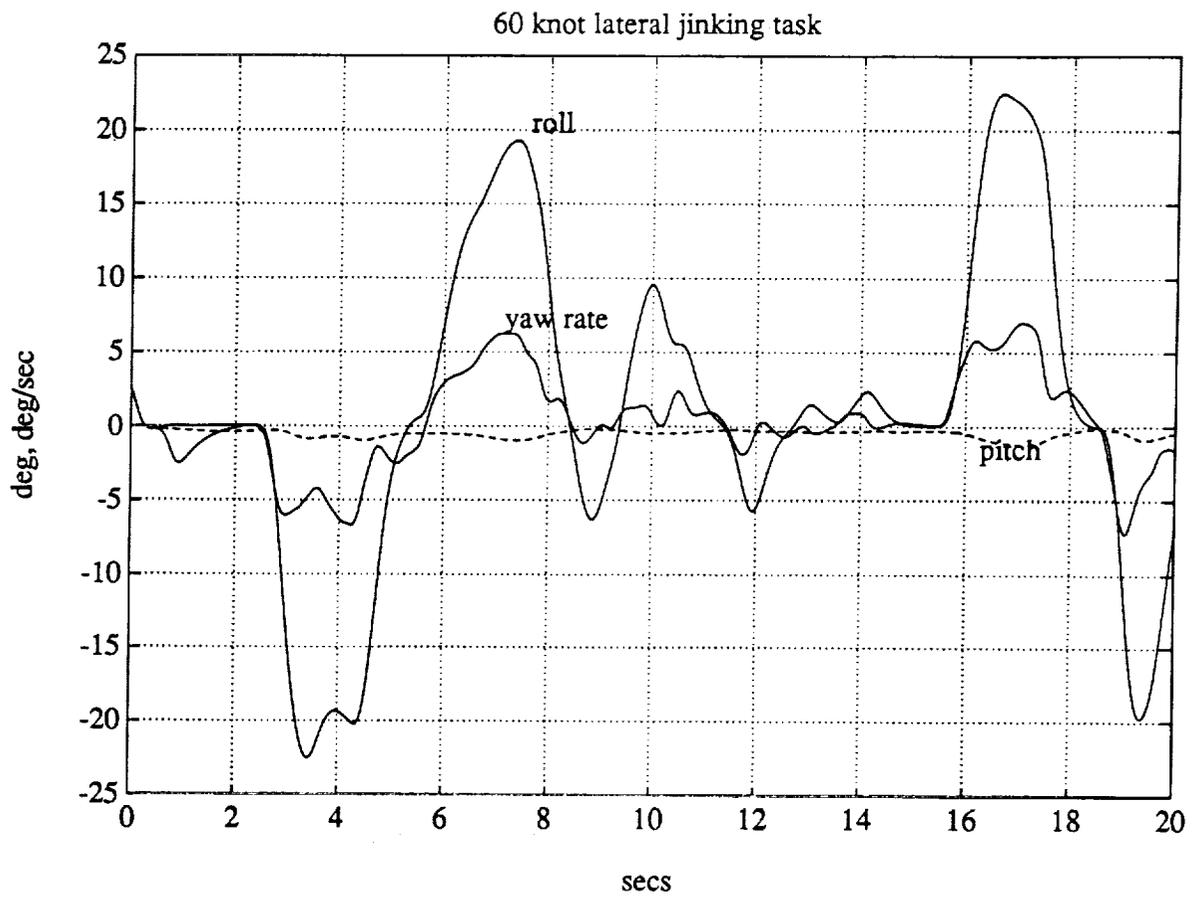
Figure 8 - Lateral jinking task data

CONCLUSIONS

Results have been presented for the piloted simulation and handling qualities analysis of a multivariable control law design for a typical combat helicopter. Through this study we have been able to demonstrate:

• Assimilation of handling qualities requirement specifications into control law design parameters.

• Robust stabilization of the aircraft with respect to changes in flight condition, model uncertainty and non-linearity.

• High bandwidth attitude command response with almost total decoupling between primary controlled outputs.

• Level 1 Cooper-Harper pilot ratings for a number of aggressively performed mission task elements.

• Compliance with many ADS-33C Level 1 requirements.

The controller has been subjected to significant and challenging tests that have shown that multivariable synthesis techniques offer considerable potential in the rotorcraft field.

ACKNOWLEDGEMENT

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