

# Modelling, Design and Rapid Prototyping of Control Laws for the Bell-412 Advanced Systems Research Aircraft

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**Key words:** helicopter control systems, handling qualities, simulation, flight mechanics models

**Abstract:** The paper presents a summary of results from a project that has involved the development of flight mechanics models and control laws for a fly-by-wire research helicopter. The aim of the project was to investigate the application of advanced control to the design of helicopter control systems meeting future combined handling qualities, structural load alleviation and flight envelope protection requirements. Over a three-and-a-half year period, two nonlinear models of the Bell 412 helicopter were developed, one in the Matlab/Simulink environment, the other in FLIGHTLAB, a specialized rotorcraft modelling software package. A Bell 412 HP helicopter with a full authority digital programmable flight control system was used to flight-test a number of new control laws. The initial modelling efforts went into the development of a simulation based on a constant rotor-speed formulation; engine and rotor-speed degrees-of-freedom were later added to the model. Some of the results obtained using that model are presented in this paper, together with results from the flight testing of several new control laws. Predictions of key handling qualities parameters including bandwidth and attitude quickness made using the new models have been very close to the true parameters identified in flight: i.e. within a few percent.

## 1 INTRODUCTION

Interest in the application of robust multivariable control techniques to helicopters dates back to the work of Tombs, Yue and Postlethwaite [1,2,3] in the mid 1980s. They applied  $H_\infty$  optimal control theory to the design of full-authority control laws using simulation models of the Lynx helicopter. The aim was to provide robust stabilization and improved handling qualities with respect to what was achievable using classical-type control laws typical of those found on production aircraft. During the 1990s this research was furthered in [4,5] with the application of the single- and two degree-of-freedom (DOF)  $H_\infty$  loop-shaping theories of [6] and [7]. Using similar models of the Lynx helicopter to those used in [1-3], assigned Level 1 handling qualities were recorded in piloted simulation trials; see [5].

The opportunity to test an  $H_\infty$  control law in flight on a helicopter came about through collaboration with the National Research Council (NRC) of Canada. NRC had converted several helicopters including a Bell 205 (Fig. 1) and a Bell 412 (Fig. 2) for use as airborne simulators. Each is equipped with a full-authority programmable digital flight control system that can be used to test experimental control laws.



*Fig. 1 Bell 205 Airborne Simulator*



*Fig. 2 Bell 412 Advanced Systems Research Aircraft*

A flight mechanics model of the Bell 205 helicopter was developed and a set of control law designs broadly similar to those described in [5] was developed using this model. Several of these control laws were implemented on the flight control computer of the NRC Bell 205 in the C programming language. The first ever test on a helicopter of a multivariable control law designed using  $H_{\infty}$  is described in [8]. Level 2 handling qualities (see [9]) were achieved. Modifications to the design process, described in [10], led to various improvements and the meeting of the Level 1 short-term frequency response requirements of ADS-33 [11], the Military Rotorcraft Handling Qualities Specification.

## **2 HELI-ACT PROJECT**

The research described in the previous section used relatively simple models of the helicopter dynamics. The rotor dynamics were modelled using disc actuator theory with linear aerodynamics. Disc tilt and coning degrees of freedom were modelled using second-order systems. The correlation between simulation-based predictions and flight tests was at times quite poor, and the flight-testing of control laws was fairly unpredictable. The indications were that more accurate models would be required if further progress was to be made. In addition, the constraints imposed by vehicle structural and other limits had been beyond the scope of the work.

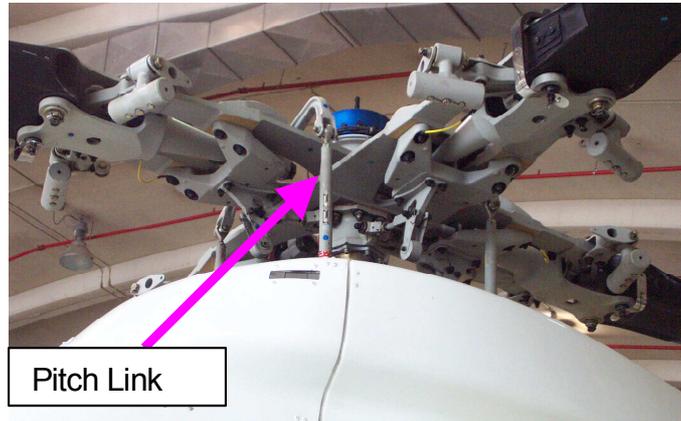
A new project known as HELI-ACT (Helicopter Active Control Technology) was therefore embarked on. HELI-ACT ran from 2003 to 2007. Its aim has been to develop new, more sophisticated simulation models and with them, novel and potentially improved controller design tools that allow more realistically posed design problems to be addressed. The aim of HELI-ACT has been to develop more sophisticated models of the flight dynamics and to use these to investigate the control issues associated with structural load alleviation and flight envelope protection. This paper presents key features of some of the new designs that have been tested on the NRC Bell 412. The HELI-ACT project has also extended the scope of previous work by bringing active structural load alleviation (SLA) and flight envelope protection (FEP) into the frame. The test vehicle that has been used, i.e. the NRC Bell 412 Advanced Systems Research Aircraft (Fig. 2) is a more agile and powerful helicopter than the Bell 205. It is equipped with rotor-blade instrumentation that enables blade flap and lag to be measured and recorded in-flight, and this has allowed some investigation of rotor state dynamics. Concerning control system design, progress has been made developing multi-objective control design tools that combine ADS-33 handling qualities requirements with SLA metrics; preliminary results have been presented in [12]. Automatic envelope protection has also been investigated; some results on torque protection are presented in section 3.3 of this paper.

### **2.1 Model development**

During the project, flight mechanics models of the Bell 412, Bell 205 and Sikorsky UH-60 helicopters have been developed. The primary software modelling tool was FLIGHTLAB, a proprietary multi-body dynamics modelling package developed by Advanced Rotorcraft Technology Inc. Separate models of the Bell 412 and UH-60 have also been developed in the MATLAB/SIMULINK environment. FLIGHTLAB offers the advantage of its in-built rotorcraft-specific libraries. It is also the software that interfaces to the University of Liverpool HELIFLIGHT flight simulator. SIMULINK on the other hand is the industry and academia standard for systems and control work and provides enormous flexibility in terms of designing, testing and rapid prototyping of control laws. All the new rotorcraft models use an individual blade-element formulation of the rotor dynamics. This essentially means that the dynamics and aerodynamics of each blade are computed individually. The helicopter models all feature blade flap and lag and inflow degrees of freedom. The Bell 412 FLIGHTLAB model has been further developed by including dynamic stall effects and components to model certain loads, principally, the pitch link load. The pitch links on the Bell 412 are shown in Fig. 3. The Bell 412 FLIGHTLAB (referred to as the FB412) model also features a partially validated model of the engine and drive-train dynamics though as will be seen later, these dynamics have proved difficult to capture. By the end of the project, the FB412 model consisted of modules representing:

- Articulated rotor with equivalent hinge offsets and spring stiffness
- Flapping and lag degrees of freedom
- 2-D Quasi-steady/unsteady air loads
- Peters-He finite state inflow equations with wake distortion
- Bailey tail rotor equations

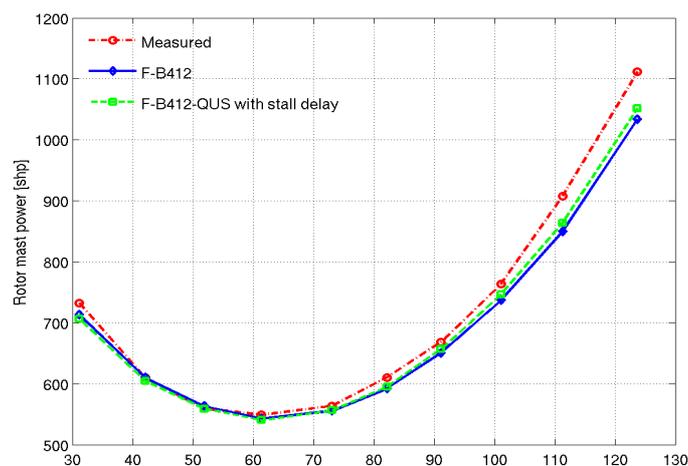
- Fuselage and empennage look-up tables
- Spring-loaded tail with Gurney flap at trailing edge
- Linear Lag Damper
- Pitch link load dynamics
- Engine and drive-train dynamics



*Fig. 3 NRC Bell 412 rotor hub showing pitch link*

## 2.2 Model Validation

The FB412 model has been partially validated using flight test data from the actual aircraft. Fig. 4 shows power required in straight-and-level flight versus speed. Fig. 5 shows the response to collective input, with the responses of the model superimposed on data gathered in flight. Collective input causes the aircraft initially to climb. Note the power and rotor-speed fluctuations. Fig. 6 shows the response to lateral stick input and Fig. 7 the rotor flapping response. The on-axis predictions are generally very good. Off-axis predictions are less good; see for example pitch rate ( $q$ ) due to lateral input in Fig. 6. Fig. 8 shows the improvement in off-axis prediction brought about by applying the MMLE3 system identification algorithm to tune one of the linearizations. The primary response (pitch rate) and the off-axis responses (roll and yaw rates) are all improved using this 'black-box' identification technique.



*Fig. 4 Trim power versus speed*

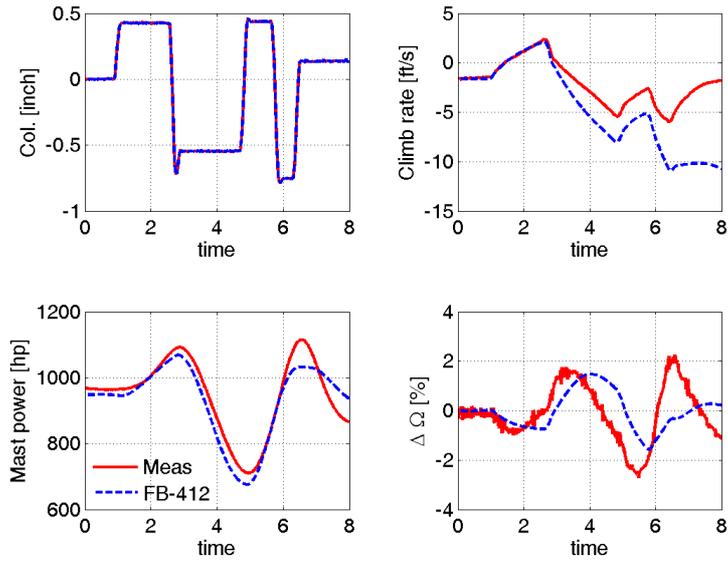


Fig. 5 Collective stick input (18kt TAS); rate of climb; mast power; rotor speed perturbation with respect to nominal.

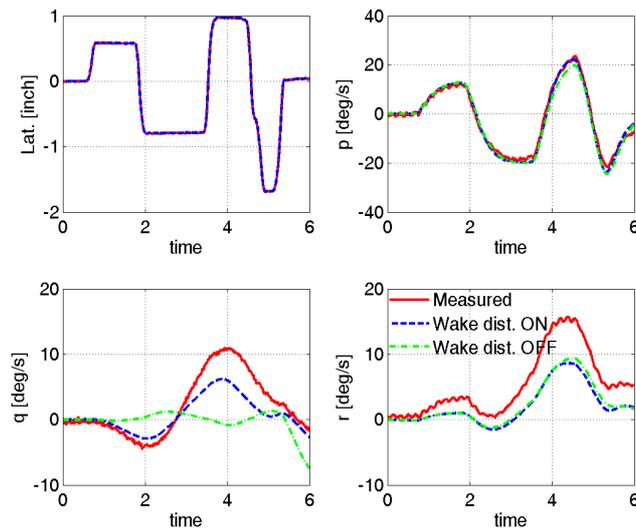


Fig. 6 Lateral stick input (15kt TAS); roll rate ( $p$ ); pitch rate ( $q$ ), yaw rate ( $r$ )

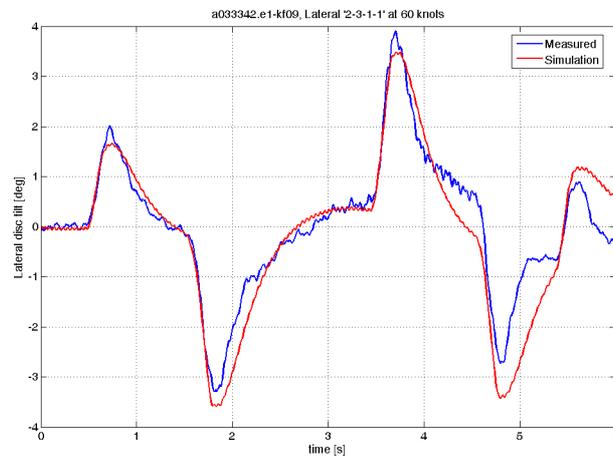


Fig. 7 Lateral disc tilt due to a lateral 2-3-1-1 input (60kt TAS)

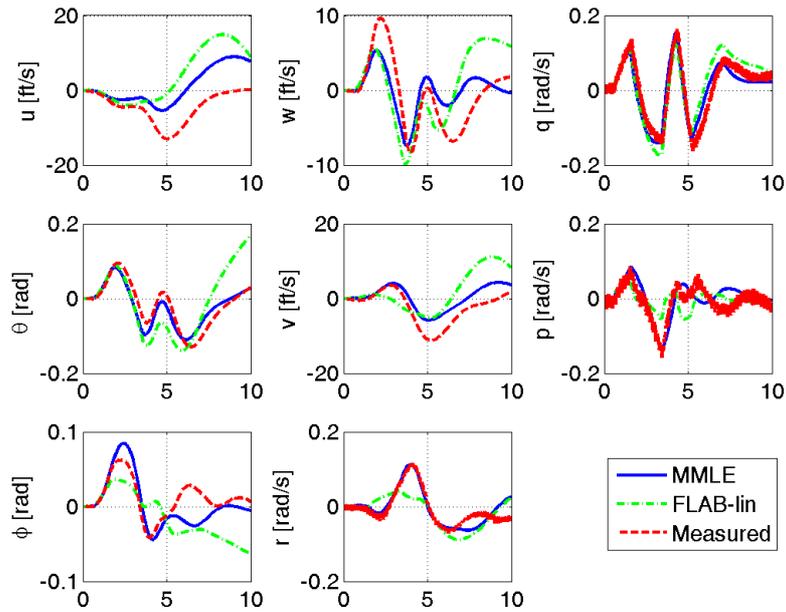


Fig. 8 Comparison of FLIGHTLAB and identified linear model responses against flight test data for a longitudinal input

### 2.3 Engine and Governor Dynamics

A block diagram model representing the engine and governor dynamics was developed by NRC. It is shown in Fig. 9. This model was incorporated into the FB412 model, and some preliminary validation work was undertaken. Linearizations from the resulting model were used as the basis for the torque-limiting control law design discussed in section 3.3.

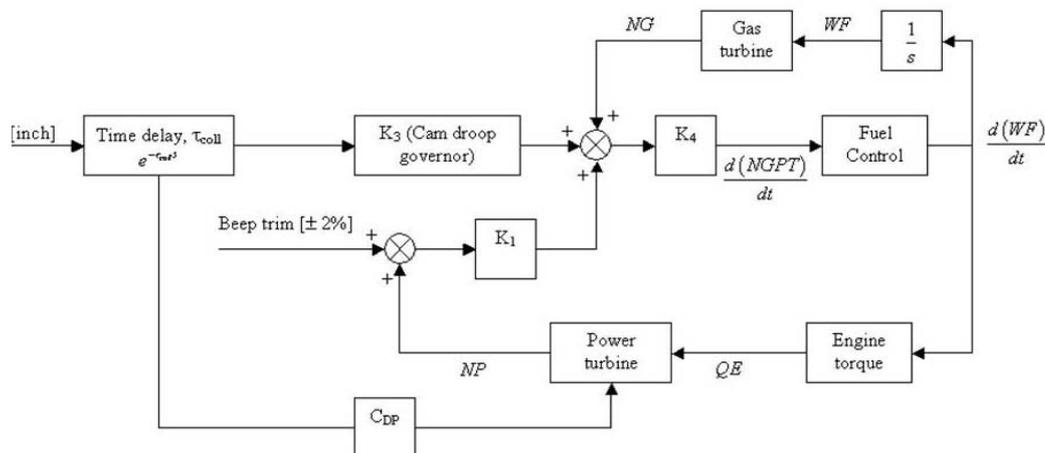
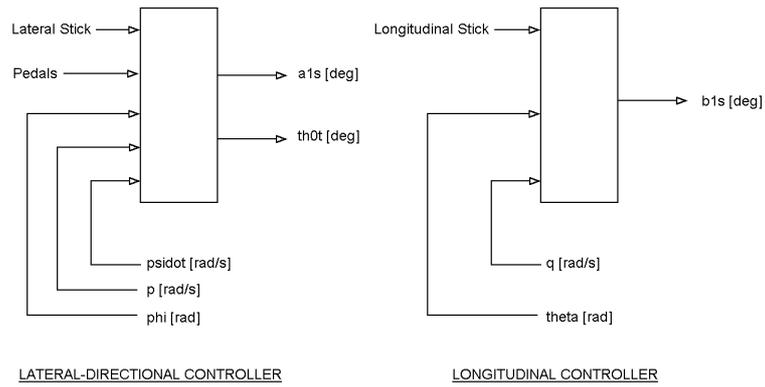


Fig. 9 Engine and Governor Dynamic Model

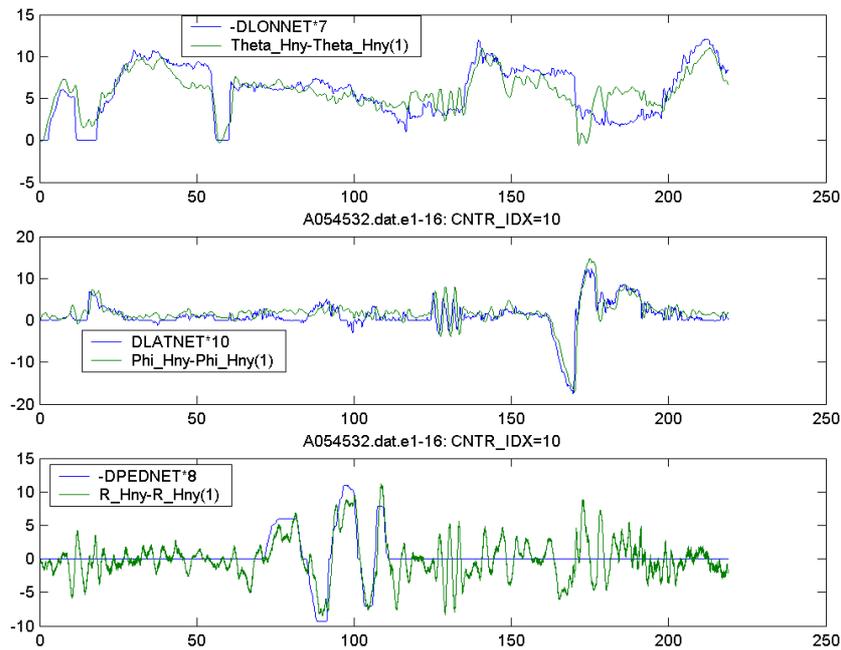
## 3 CONTROL LAW DESIGNS FOR THE BELL 412

### 3.1 H-infinity ACAH Control Law

A system was designed using  $H_\infty$  optimal control to provide an attitude-command, attitude hold response type in pitch and roll axes and a rate response type in yaw. The control law comprised separate lateral/directional and longitudinal sub-systems as shown in Fig. 10. These were designed in such a way that the deflections of the cockpit controls (longitudinal and lateral stick and pedals) defined the demands of pitch and roll attitude and yaw rate, respectively. The control law equations which were essentially of the form  $\dot{x} = Ax + bu$ ,  $y = Cx + Du$  were hand-coded in C and the system flight-tested. Fig. 11 shows data from the test of this controller.



*Fig. 10  $H_\infty$  Control Law Architecture*

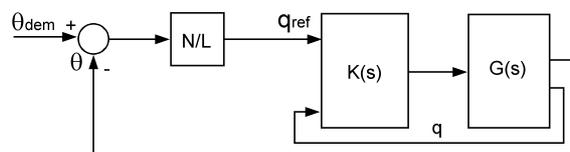


*Fig. 11 Flight-test of  $H_\infty$  control law showing primary responses with references superimposed*

The aim of this test was principally to check that all hardware and software systems were working, and that there were no problems with sign conventions, controller implementation and the like. The performance of the controller in pitch and roll was reasonably good, though the yaw axis response was ratchety and adversely affected by the engine/collective/rotor speed dynamics.

### 3.2 ACAH Control Law with Pitch Axis Non-linearity

The enhanced stability provided by an attitude command system tends to be at the expense of agility for medium and large control inputs. Therefore several pitch axis control laws were investigated with the aim of recovering some of the lost performance. One such architecture is depicted in Fig. 12. It consists of an inner rate loop driven by an outer attitude feedback loop containing a static nonlinearity designed to maximize or at least, to specify the pitch rate.



*Fig. 12 Nonlinear Pitch Axis Control Law*

Several pitch axis control laws based on this architecture were flight tested. Fig. 13 shows the pitch attitude ( $\theta$ ) response of one such control law to a nose-up pitch attitude demand. The traces on the graph show the attitude demand (---) and the response (-). Cross-coupling between pitch and roll was of order 5%; however there is uncommanded yaw rate arising from a coupling between the yaw and collective (vertical) axes and the engine dynamics that is not well captured by the model. Analysis of the data shows that the desired pitch rate was consistently achieved. By analysing various portions of the flight data record, the attitude quickness  $Q_\theta$  (Fig. 14) can be plotted; it is seen that the data points (\*) coincide closely with the theoretical value (---) specified by means of the non-linear element.

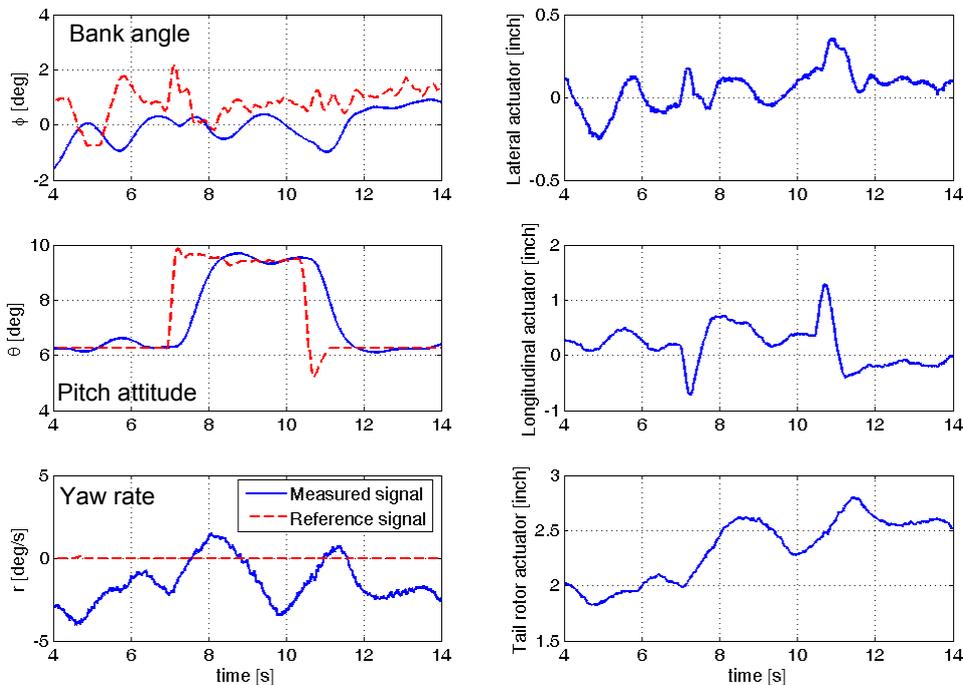


Fig. 13 Flight test MV001B - longitudinal stick inputs at 20 knots forward flight (A064912.dat.e1-11)

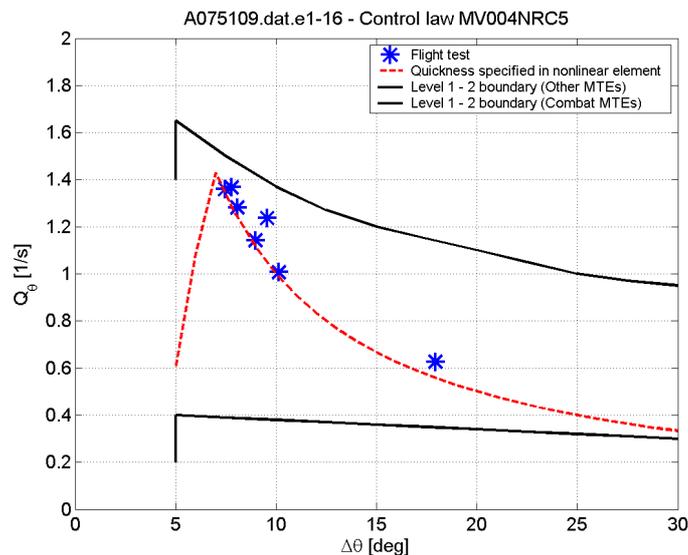


Fig. 14 Specified and achieved attitude quickness ( $= \max. \text{pitch rate/pitch attitude change } q_{\max} / \Delta\theta$ )

### 3.3 Torque-Limiting Control Law BM003

Fig. 15 shows a system architecture that was proposed to improve the oscillatory torque response on the Bell 412. The control law  $K(s)$  was designed using linearizations from the FB412 model containing

engine dynamics. Fig. 16 is a handling qualities chart relating to ADS-33E-PRF transient torque requirements, on which the simulation-based data predict an improvement from Level 2 without the controller to Level 1 with it. Note that the predictions in Fig. 16 are based on simulations.

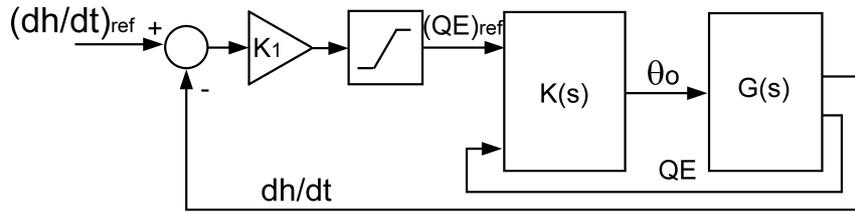


Fig. 15 Block diagrams for Torque (QE) Protection System

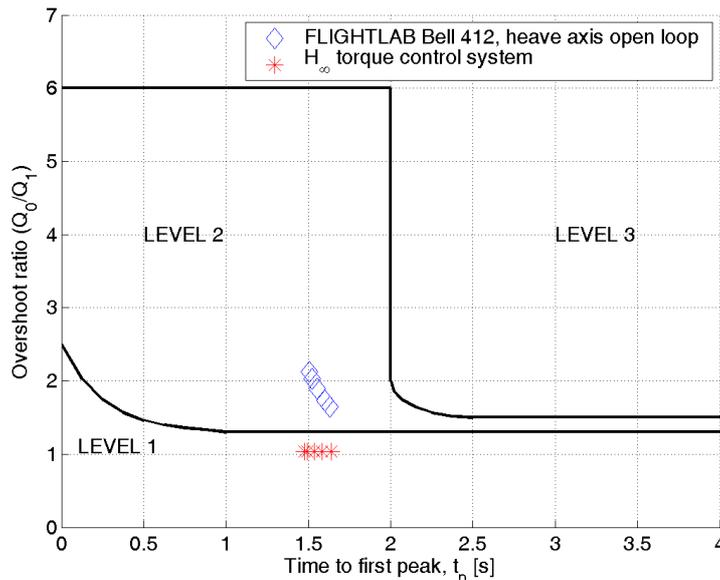


Fig. 16 ADS-33 Torque Response Criteria

The BM003 control law was tested in flight. The torque limit was set at 80%. However the system was unable to enforce this limit, as shown in the portion of flight test data reproduced in Fig. 17. The reason for this is not currently known.

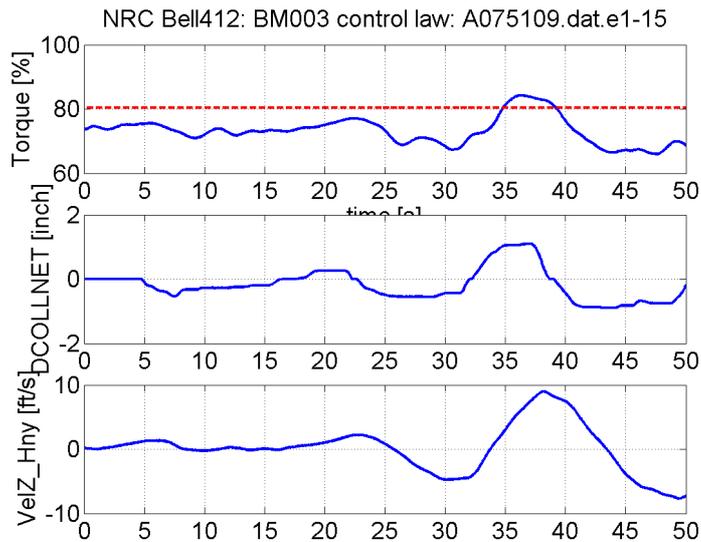
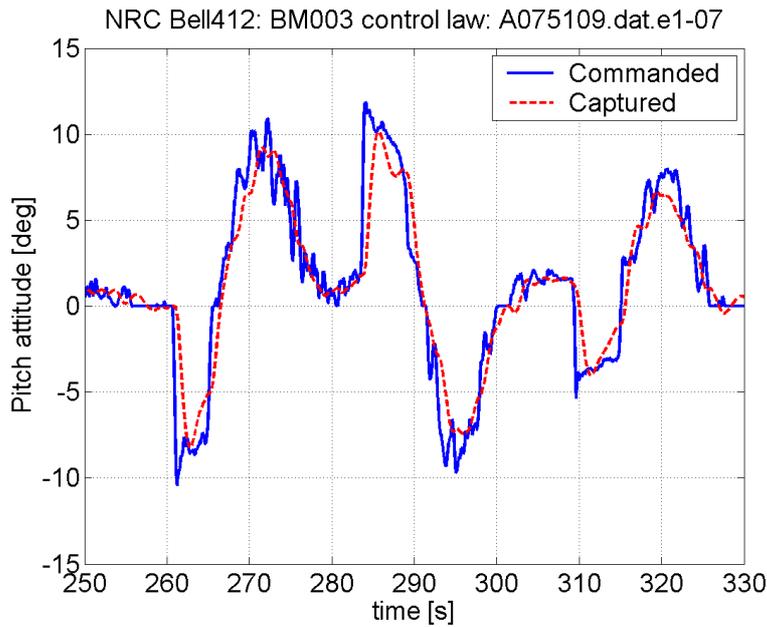


Fig. 17 Torque, collective and vertical velocity responses of BM003 torque-limiting controller

Pitch and roll attitude control exerted by the BM003 controller was much more satisfactory; the pitch axis response is shown in Fig. 18; the commanded attitude is accurately captured.



*Fig. 18 Pitch Axis Response of BM003 Control Law*

Most of the controllers tested on the ASRA during HELI-ACT were hand-coded in C for implementation on the flight control computer. However with BM003 it was felt that the complexity of the control laws had reached the point where it was more sensible to auto-code the control laws using MATLAB Real-time Workshop. Processes and software to allow this were accordingly developed.

#### 4 FREQUENCY DOMAIN COMPARISON OF CONTROLLERS

Table 1 shows the closed-loop bandwidth, calculated in accordance with definitions given in ADS-33E-PRF [11] for three controllers designed during the project. The new models have enabled extremely accurate predictions of this and other key handling qualities parameters to be made.

BM003	Bandwidth [rad/s]		Phase delay [s]		HQ Level (Predicted) (Non-combat MTE)
	Flight	Predicted	Flight	Predicted	
Roll	4.34	4.48	0.09	0.05	1
Pitch	2.18	2.62	0.11	0.06	1
Yaw	2.62	2.72	0.20	0.02	1
FCL001					
Roll	3.80	3.70	0.12	0.06	1
Pitch	1.80	1.60	0.37	0.21	1
Yaw	2.40	2.40	0.05	0.02	1
DW001					
Roll	4.10	4.20	0.097	0.07	1
Pitch	3.10	3.10	0.148	0.06	1

*Table 1. Closed-loop bandwidth and phase delay for three different control laws: achieved in flight versus predictions based on linear models*

## 5 CONCLUSIONS

Tools have been developed for flight control law design that exploit several new hi-fidelity rotorcraft models. These tools have been used to design and test a variety of control laws using a mix of classical linear and nonlinear control techniques and robust  $H_\infty$  optimal control and  $\mu$ -analysis. We have combined non-linear elements with linear stabilization schemes in such a way as to recover some of the moderate-amplitude performance (agility) that is otherwise sacrificed for improved stability and damping. The resulting unconventional response-type has been subjected to piloted simulation and it has been favourably greeted. The concept has also been demonstrated in flight. This is the first time such tests have taken place on a rigid-rotor helicopter.

A torque-protection control scheme has also been proposed. However, the collective, rotor-speed, torque, heave, and yaw interactions are complex and currently not well modelled and this is likely to be behind the failure of the torque protection scheme to operate as intended. This is the subject of ongoing research. Overall however, the FB412 model represents without doubt a significant step forward in terms of fidelity and validation, in relation to the models used in support of previous UK research into helicopter flight control.

## 6 ACKNOWLEDGEMENTS

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