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FLIGHT TEST OF A NONLINEAR CONTROL LAW ON THE BELL 412 ADVANCED SYSTEMS RESEARCH AIRCRAFT

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ABSTRACT

The design and initial flight-test of two nonlinear flight control laws for the Bell 412 Advanced Systems Research Aircraft is presented. Both control laws are nonlinear in one axis and provide an attitude command attitude hold response type. Nonlinear elements are used to specify the speed of response and thus the attitude quickness of the flight control laws. Piloted simulation indicated that an attitude command attitude hold response type with a fixed speed of response was pleasant because it is very predictable. The performance in the nonlinear axes was set to be relatively low in the flight test because the purpose of the first flight test was to test the concept and to determine how well the nonlinear stability analysis techniques stood up in practice. In the first flight test, the controllers gave a stable closed-loop and provided the required response-type. Describing function analysis proved to be a useful nonlinear stability analysis technique, which could be combined with relative stability requirements from MIL-F-9490D. Closed-loop bandwidth predictions based on linear frequency domain analysis using a 28-state linear model of the Bell 412 correlated closely to the bandwidths achieved in flight, determined with frequency sweeps.

1 INTRODUCTION

The intentional introduction of nonlinear elements in a control system can result in superior system characteristics [1]. One of the requirements in the Aeronautical Design Standard Performance Specification Handling Qualities (HQ) Requirements for Military Rotorcraft, also known as ADS-33-PRF [2], relates to *attitude quickness*: a measure of the agility with which a rotorcraft can change its attitude or heading. The present paper shows how a nonlinear control element can be combined with a linear attitude command attitude hold (ACAH) control law to shape the response, such that a pre-specified attitude quickness is achieved. At the same time, it places an upper bound on the control activity (actuator travel). This method may potentially be used to maximise the agility whilst providing an ACAH response type. It can also be used as a means of harmonising the response characteristics to inputs in the longitudinal and lateral axes. Control harmony is arguably one of the most important aspects of flying qualities [3]. Another application may be the implementation in an autopilot in order to give the system smooth ride characteristics. The first linear control law tested in conjunction with the nonlinearity is a classical controller. The second is designed with the H_∞ loop-shaping design procedure [4].

A second goal of the research is to determine which nonlinear stability analysis techniques are of practical use when it comes to the design and optimization of flight control laws containing nonlinearities. A conservative stability criterion might, in theory, unnecessarily limit the performance of the system. This will be applicable to future work, in which we aim to develop optimized control laws for height control, torque envelope protection and translational rate command (TRC). The TRC control laws use an ACAH inner loop system. The attitude reference signal is based on a translational rate error. This attitude reference will have to be limited with a nonlinear element because a large translational rate error could result in a very large attitude reference signal, which is undesirable. Another example, which is the area of current research, is the development of a height-hold system with torque envelope protection. The inner loop of this control law is a torque command system and the torque demands from the height hold will have to be limited to prevent torque excursions. So, nonlinear elements can and will be used for several applications.

The work presented in this paper is performed within the HELI-ACT (Helicopter Active Control Technology) project, which involves collaboration between the University of Liverpool (UoL) and the National Research Council (NRC) of Canada. Use is made of a sophisticated six-axis motion base Flight Simulator (HELIFLIGHT) at the University of Liverpool (Fig 1.1), and the Advanced Systems Research Aircraft (ASRA) [5],[6], a Bell 412 fly-by-wire research helicopter, operated by the NRC (Fig 1.2).

Figure 1.1: Flight simulator at the University of Liverpool

Figure 1.2: Bell 412 Advanced Systems Research Aircraft (ASRA), operated by NRC Canada

This project has two strands, one related to model development, the other to active control for handling qualities, flight envelope protection and structural load alleviation (HQ, FEP and SLA). The focus in the present paper is on Handling Qualities improvement with ‘novel’ control techniques. The control theory itself is not novel, however the application of it as presented in this paper is considered to be novel.

This paper is organised as follows. The Bell 412 ASRA and the nonlinear simulation model of it are described in section 2. The nonlinear flight control laws to be tested on this aircraft are subsequently treated in the third section. These control laws are then subjected to an offline analysis (section 4), a limited piloted simulation trial (section 5) and finally an actual flight test (section 6). Section 5 also includes a brief description of the HELIFLIGHT flight simulator. Conclusions and recommendations are made in the final section.

2 BELL 412 ADVANCED SYSTEMS RESEARCH AIRCRAFT

The Bell 412 ASRA, operated by the NRC Canada is equipped with a full-authority simplex experimental fly-by-wire system [7]. The simplex architecture allows:

- a single set of FBW actuators;
- one, non-redundant flight control computer;
- a single set of aircraft state sensors; and
- a single set of flight control software.

The simplicity of this design facilitates the incorporation of software changes without the overhead of multiple coding sources, multiple languages or operating systems and in-depth code validation. These overheads are necessary for production systems, but are overly prohibitive for flexible, time critical research programs. Inherent to the design philosophy of ASRA's simplex architecture is a reliance on automated safety monitoring systems (Health Monitoring Unit) and a safety pilot to guard against system failure or operational flight envelope exceedance. This requires an increased reliance on the safety pilot and adds to his workload. However, the combination of the safety pilot and an automated safety monitoring system allows for FBW engaged flight in the entire certified operational flight envelope. The ASRA control system structure, as shown in figure 2.1, consists of both safety pilot and evaluation pilot control paths. The safety pilot flies the helicopter using the certified mechanical control system, and is responsible for assuming control in the event that a computer malfunctions or a potentially dangerous situation arises. The evaluation pilot's controls, when engaged by the safety pilot, control ASRA through a fully programmable, full authority fly-by-wire control system. A wide range of flight parameters are measured and stored by the flight control computer (FCC) at a data rate of 128 Hz. In addition, these parameters are available to use as feedback values in various aircraft control system schemes. Conventional parameters such as aircraft angular rates and attitudes are measured as well as more unconventional parameters such as rotor flapping angles, angle of attack, angle of sideslip and more. The control power and bandwidth of the rotor system is similar to that of standard production helicopters [5]. High bandwidth flight control systems can therefore be tested on the ASRA. This flexible structure of the fly-by-wire system is such that new control laws can be implemented and tested rapidly on the system. This makes the ASRA an ideal platform for research into novel control concepts for helicopters.

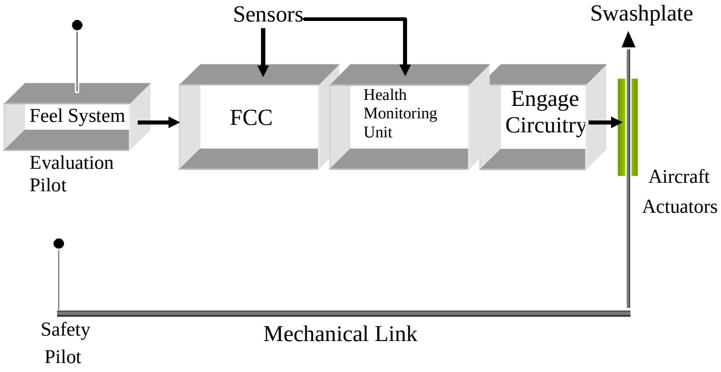

Figure 2.1: ASRA Control System Structure Schematic

A high fidelity nonlinear simulation model of the Bell 412 ASRA has been developed previously within the HELI-ACT project [8]. The comprehensive real-time simulation program FLIGHTLAB [9] was used for this. This model, designated FB412, uses a rigid blade-element main rotor. The air loads acting on the blade elements are calculated with quasi-steady aerodynamics. The Peters-He finite state inflow model was used [10]. A Bailey rotor model represents the tail rotor [11]. Aerodynamic look-up tables represent all fuselage aerodynamics, the vertical fin and the horizontal tail plane. The data required for the development of this model was partly acquired from literature in the public domain and partly by measurements performed on the ASRA at the NRC Canada. The model was validated against a set of flight test data and the main conclusion was that excellent correlation of the on-axis aircraft response was achieved between the nonlinear simulation model and the actual aircraft. However, the off-axis response correlation was not as good [8]. Work is currently in progress on the further development of the nonlinear simulation model. In parallel to this, linear aircraft models were also developed with system identification of flight test data. The dynamic response of the FB412 compared to the actual aircraft, as the result of a longitudinal stick input, is displayed in figure 2.1, to give an impression of the fidelity of the model.

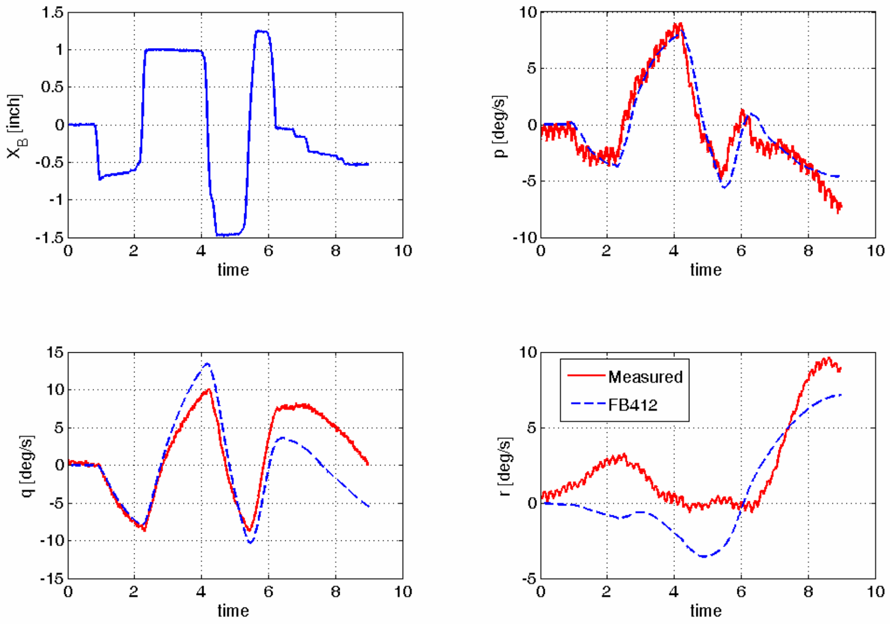

Figure 2.1: Dynamic response due to a longitudinal input

Control law design is carried out in the MATLAB/SIMULINK environment, with linear models obtained from the FB412. ADS-33-PRF [2] has been used to guide the design process. Control laws are subsequently tested offline in the linear domain. They are then implemented on the nonlinear FB412 model and subjected to offline testing, and then piloted simulation. This can take several iterations and when results are deemed to be acceptable, the control laws were subjected to a flight test on the real aircraft. For this, the control law had to be discretised and coded into C.

3 NONLINEAR CONTROL LAW DESIGN

Linear models were obtained from the FB412 nonlinear simulation model for control law design. Two nonlinear control laws were designed based on these linear models: one with a classical inner loop, the other with an inner loop designed with the H_∞ loop shaping design procedure [4]. Both control laws are designed with the ADS-33 handling qualities specification in mind. The linear models are briefly treated in the next sub-section, followed by the description of the two control laws in sub-sections 3.2 and 3.3.

3.1 Linear model of the Bell 412

A set of 9-state and a set of 28-state linear models were obtained from the FB412 nonlinear simulation model for the complete speed envelope at intervals of 10 knots. Handling qualities are strongly influenced by the stability of the natural modes [3]. The eigenvalues of the 9-state linear models as a function of airspeed are presented in figure 3.1.

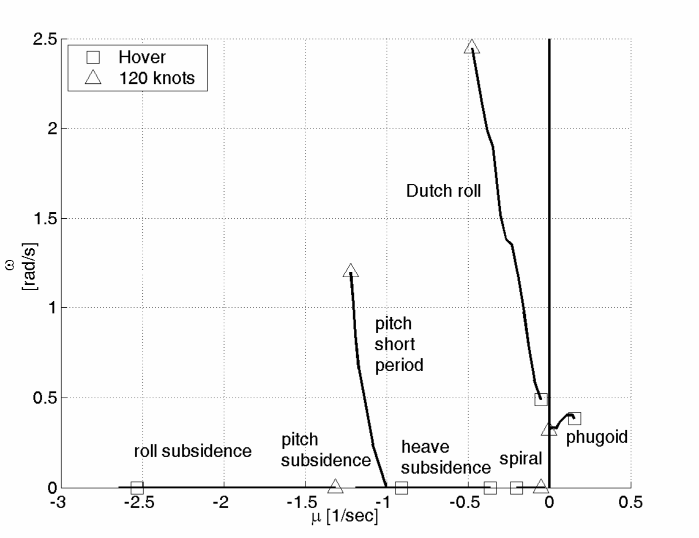

Figure 3.1: Variation of eigenvalues of the bare airframe FLIGHTLAB Bell 412 ASRA with forward speed

One can see that the phugoid-like mode is unstable over almost the complete speed range. The other modes are stable. However, the Dutch roll mode is lightly damped. In terms of ADS-33 handling qualities, this would be described as Level 2. The phugoid-like mode is even on the border of the Level 3 region at hover. The term ‘phugoid’ is something of a misnomer at hover and low-speed, since the mode is quite different from the classical fixed-wing phugoid in which airspeed is traded for altitude and vice-versa. The linear model used for control law design is derived at 10 knots forward level flight and contains the 9 rigid body states. This flight condition is chosen because it is the most challenging condition to the designer due to the unstable characteristics of the helicopter and the rapid change in dynamics in the neighbourhood of hover [12].

3.2 Flight control law 1 (FCL001)

This control law is a classical decoupled controller providing an ACAH response type in the roll and pitch axes, a rate command (RC) response type in yaw and the heave axis is left open loop. All sub-controllers are designed with classical proportional plus integral (PI) control except for the pitch axis sub-controller. This sub-controller has a high bandwidth inner loop (3.9 rad/s) providing pitch ACAH and an outer loop with a nonlinear element in it (Fig 3.2).

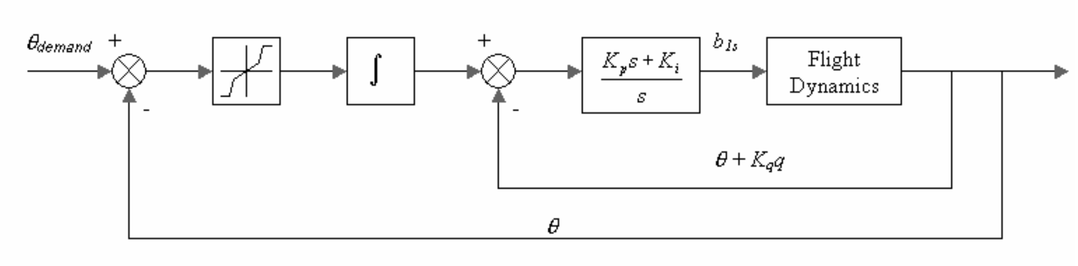

Figure 3.2: Structure of the longitudinal sub-controller of FCL001

The nonlinear element determines the speed of the response in the pitch axis and allows the designer to shape the attitude quickness in this axis. The speed of response is set to 15 deg/s within the nonlinear element. Note that pitch rate is mixed with pitch attitude and fed back in the inner loop. This is similar to using pure pitch attitude feedback and a PID control law. However, the system is less prone to noise. The other sub-controllers have the same structure as the inner loop of the pitch sub-controller and are therefore not shown.

Three nonlinear elements were tested on the linear flight dynamics model with this control law. These were: (1) a relay, (2) a saturation and (3) a more general piecewise nonlinearity. Time domain responses of the system are shown in figure 3.3 for these three elements. The relay gave rise to limit cycle oscillations and was therefore discarded. The saturation gave a huge improvement; however some overshoot was present. The piecewise nonlinearity was similar to the saturation, but has small gain for small inputs. This gave the desired speed of response, with no perceptible overshoot. The response to different size step inputs is shown in figure 3.4.

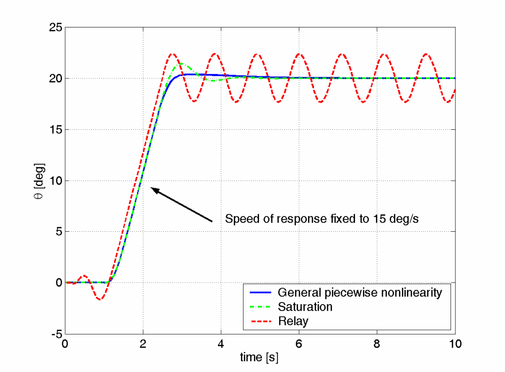

Figure 3.3: Test of different types of nonlinearities at 10 knots forward flight

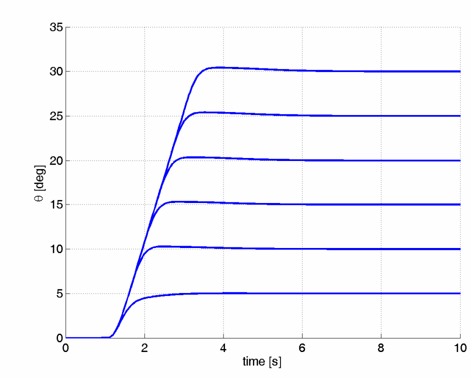

Figure 3.4: Different size step inputs with FCL001 with a general piecewise nonlinearity

Note how the speed of response is fixed to 15 deg/s, regardless of the magnitude of the input. The overshoot in the linear simulation is minimal for all inputs.

3.2 Flight control law 2 (FCL002)

The inner loop of this control law is designed with the H_∞ loop shaping design procedure [4]. The control law consists of a longitudinal sub-controller and a lateral/directional sub-controller. It was designed to give the same response type as FCL001. This time, a nonlinear element is added to the lateral axis in exactly the same manner as with the longitudinal axis of FCL001. The lateral/directional sub-controller structure is presented in figure 3.5.

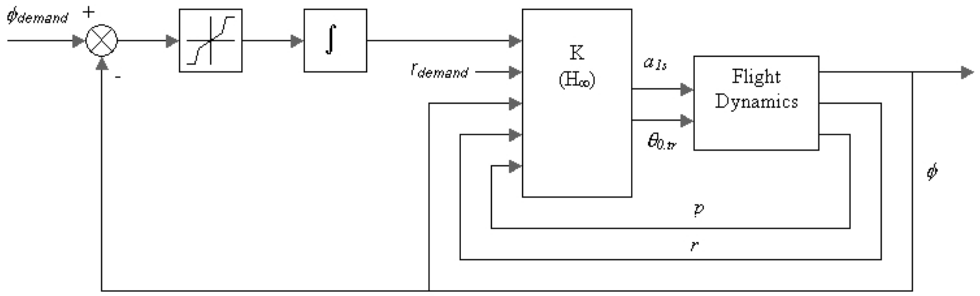

Figure 3.5: Lateral/directional control schematic FCL002

The speed of response is set to 25 deg/s within the nonlinear element. This is relatively low in terms of roll attitude quickness (Level 2 – other MTEs) and it could be set higher to at least 35 deg/s with this inner loop control law. However, as stated earlier, the aim was to test the concept of fixing the speed of the response, rather than to try to produce an optimized design. Specifying reasonably low quickness in the nonlinearity was deemed to be far more likely to result in a system that would work and provide useful data, given the complexity of the dynamics of the vehicle being controlled and the uncertainty in the model. The roll axis bandwidth of the inner loop, calculated on the linear model, is 4.2 rad/s at the 10-knot design condition. A higher bandwidth inner loop controller will allow us to increase the speed of response significantly. Another method of achieving a higher performance might be by using a rate command inner loop instead of an ACAH inner loop in series with a command path integrator. This is planned for future work.

4 OFFLINE CONTROL LAW ANALYSIS

The offline analysis of the nonlinear control laws is presented in this section of the paper. Stability analysis is presented in 4.1, followed in 4.2 by performance analysis using criteria from ADS-33-PRF.

4.1 Stability analysis

One of the most important questions when designing a control law is that of stability. Both control laws discussed above consist of an inner and an outer loop. When a linearized model represents the flight dynamics, the inner loop in Figure 3.5 is linear and the outer loop is nonlinear. The robust stability requirements from MIL-F-9490D [13] are used to determine whether the relative stability of the control law is satisfactory. These requirements are more stringent than the disturbance rejection requirements specified in ADS-33 [14]. The stability margins at the rigid body mode frequencies in terms of Gain Margin and Phase Margin are required to be larger than 6 dB and 45°. These margins have to be met for the inner loop as well as the outer loop. Conventional techniques for stability analysis cannot be directly applied to the nonlinear outer loop. To check for stability of this loop, two techniques are used in this paper: 'describing function analysis' [15] and the 'Popov Criterion' [16]. The Popov Criterion gives a sufficient condition for the global asymptotic stability of a feedback system containing a sector-bounded static nonlinearity, such as those discussed above. It provides a conservative test; in other words, the feedback system is not necessarily unstable when the Popov criterion is not met. Describing function analysis, on the other hand, is a tool for investigating the existence of limit cycles in nonlinear systems. It is also an approximate technique; it can predict limit cycles that in practice do not exist, or vice versa. Nonetheless, because it is based on frequency domain ideas and involves a simple graphical test, it has been widely used in systems and control circles for decades. The results of the nonlinear stability analysis of the outer loop of FCL001 are displayed in figures 4.1 and 4.2.

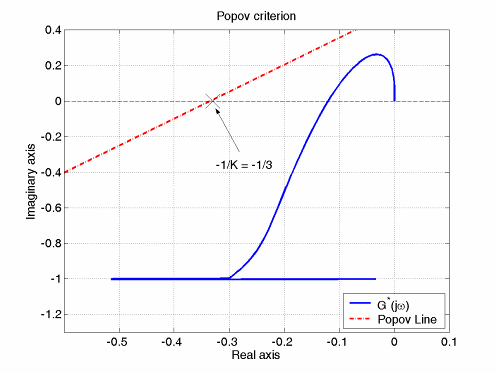

Figure 4.1: Popov criterion pitch axis FCL001 at 10 knots

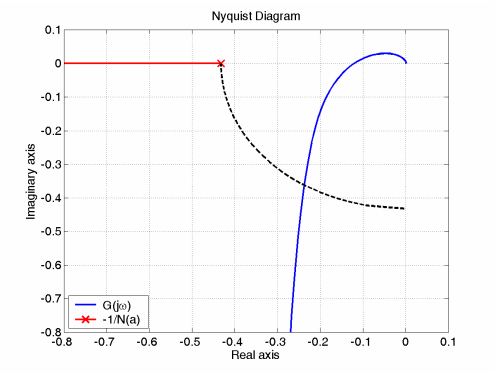

Figure 4.2: Describing function analysis pitch axis FCL001 at 10 knots

The linear part of the system (Fig 3.1 or 3.5), including the linear model of the helicopter, is called G(jω). This frequency response function can be modified to $G^*(j\omega)$, where $\mathrm{Re}\,G^* = \mathrm{Re}\,G$ and $\mathrm{Im}\,G^* = \omega\,\mathrm{Im}\,G$. The Popov criterion is met when the modified frequency response function lies to the right of the Popov line. The Popov line is a line through the point –1/K, with K being the sector bound of the nonlinearity. There are no restrictions on the slope of the line for the nonlinearity considered. The Popov line and the modified frequency response function for FCL001 are presented in figure 4.1 at the design condition. It can be concluded from this figure that the Popov criterion is met and thus global asymptotic stability of the system is proven. Describing function analysis can be performed graphically with a polar plot. A limit cycle is predicted when the polar plot of G intersects with the plot of –1/N, where N is the describing function of the nonlinearity. This limit cycle can either be stable or unstable. A phase margin and a gain margin can be calculated analogously to the Nyquist criterion for linear systems; these indicate the ‘distance’ to the limit cycle. This is done in figure 4.2 for FCL001. The describing function analysis indicates a Gain Margin (GM) of 11.1 dB and a Phase Margin (PM) of 56°, which implies that the stability margins specified in MIL-F-9490D are achieved for the outer loop of the pitch axis of FCL001. The inner loop of FCL001 was analysed with conventional techniques and it was found that the phase margins and gain margins in all axes complied with the requirements. The inner loop of FCL002 had already been tested in flight in December 2005 during a systems check on the Bell 412 ASRA and was found to be stable and flyable. Offline stability analysis is therefore not presented in this paper. The outer loop of FCL002 reveals a gain margin of 7.2 dB and a phase margin of 30°. This means that the phase margin is too low. However, the phase margin increases with speed and the MIL-F-9490D requirements are satisfied at 20 knots already. The Popov criterion is on the boundary of being satisfied for FCL002. A test in the flight simulator indicated stability of the control law over the complete speed envelope.

4.2 Predicted handling qualities

The predicted handling qualities discussed in this section were calculated with the nonlinear simulation model. The key parameter we are interested in is the attitude quickness. Recall that this parameter can be tailored with the nonlinear element.

The pitch attitude quickness of FCL001 has a hyperbola (‘1/x’) shape because the speed of response (pitch rate) is fixed by the nonlinearity. Two cases are shown in figure 4.3, one with a 10 deg/s speed of response and one with a 15 deg/s response. The speed of response can be increased until the control law becomes unstable or until the performance limits of the aircraft are reached. It is not the intention in this paper to maximize the quickness, but to prove that nonlinearities can be used in control law design in order to tailor the attitude quickness. The roll quickness of FCL002 also has a ‘1/x’ shape when the attitude error exceeds 20 degrees. The speed of response is set to be lower when the attitude error is smaller than 20 degrees in order to reduce overshoot.

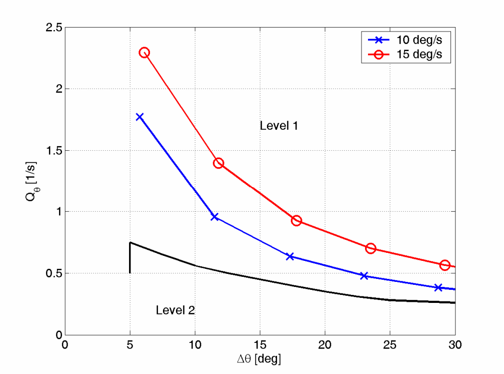

Figure 4.3: Pitch attitude quickness FCL001 – all other MTEs at 10 knots forward flight

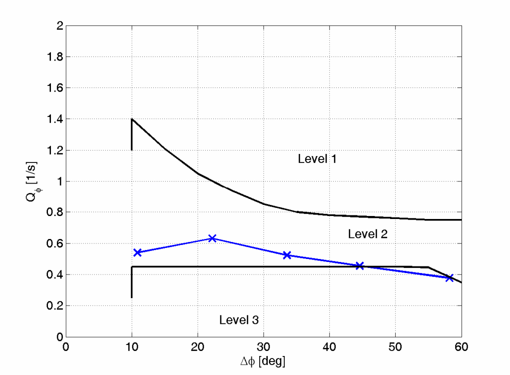

Figure 4.4: Roll attitude quickness FCL002 – all other MTEs at 10 knots forward flight

The pitch attitude quickness is of FCL001 is clearly in the Level 1 region for non-combat MTEs. Roll and yaw quickness of this control law are also both in the Level 1 region for non-combat MTEs. The roll quickness of FCL002 is in the Level 2 region for non-combat MTEs and the quickness of the other axes of FCL002 (not shown here) is Level 1 for non-combat MTEs

The bandwidths and phase delays of both control laws were calculated in the linear domain from frequency response analysis with the 28-state linear model at the 10-knot design condition.

Controller	ω_{BW} [rad/s]	τ_p [sec]	Handling Quality	
			Combat	Other
Pitch				
FCL001 (nonlinear)	1.6	0.21	2	2
FCL002	3.9	0.07	1	1
Roll				
FCL001	4.2	0.071	1	1
FCL002 (nonlinear)	1.6	0.25	3	2
Yaw				
FCL001	2.5	0.022	2	1
FCL002	2.2	0.01	2	1

Table 4.1: Bandwidths of FCL001 and FCL002 on the 28-state linear model at 10 knots

All the bandwidths are Level 1 for non-combat manoeuvres except for the two nonlinear control loops. The roll axis bandwidth of FCL002 is Level 2 and the pitch axis bandwidth of FCL001 as well. One remark has to be made here; the bandwidth for these axes is a function of the input size due to the presence of the nonlinearity. The bandwidths shown here are for small inputs.

Finally, inter-axis coupling criteria were checked. All criteria considered (pitch due to roll, roll due to pitch and yaw due to collective) were found to be well within the Level 1 region.

In summary, the predicted handling qualities of FCL001 are Level 1 when non-combat MTEs are considered except for the bandwidth in the pitch axis. The attitude quickness drops below the Level 1-2 boundary for combat MTEs in all three axes. This analysis gave the confidence that FCL001 could be tested with a pilot in the loop. The predicted handling qualities of FCL002 are Level 1 for non-combat MTEs in all cases, except for the quickness and bandwidth in the roll axis, which are both Level 2.

5 PILOTED SIMULATION

The flight simulator HELIFLIGHT [17] at the University of Liverpool is used for piloted simulation. This system is the main research and simulation tool of the Flight Simulation Laboratory (FSL). It is a re-configurable flight simulator with five key components that are combined to produce a high fidelity system, including:

- Selective fidelity, aircraft-specific, interchangeable flight dynamics modelling software (FLIGHTLAB) with a real time interface (PilotStation),
- Six Degree Of Freedom motion platform (Maxcue),
- Four-axis dynamic control loading (Loadcue),
- Three channel collimated visual display for forward view, plus two flat panel chin windows, providing a wide field of view visual system (Optivision), each channel running a visual database,
- Re-configurable computer-generated instrument display panel and head up display.

FCL001 was subjected to a limited piloted simulator trial in order to test the overall system with a pilot in the loop and to obtain feedback on the ACAH system with a constant speed of response, generated by the presence of the nonlinearity. The performance of the inner loop was set to be higher than in the flight test. The reason for this is that the aim of the trial was to gain feedback on the ACAH system with a constant speed of response. It was already clear that the control law was stable in the real-time simulation environment. It was decided to perform three mission task elements, which together test the performance of the control law in all axes. The selected MTEs are: (1) acceleration-deceleration, (2) sidestep and (3) slalom. A thorough description of these MTEs can be found in ADS-33 [2]. The results of this trial, in terms of Cooper-Harper Handling Qualities Ratings (HQR) [18], are summarized in table 5.1.

ADS-33 Mission Task Element	Cooper Harper Handling Quality Rating
Sidestep	2
Acceleration Deceleration	4
Slalom	4

Table 5.1: Handling qualities ratings obtained in piloted simulation with FCL001 with a high performance inner loop

Both the sidestep and the acceleration-deceleration are quite difficult manoeuvres in the simulator. According to the pilot, the HQR awarded for the acceleration-deceleration MTE could be better if the field of view in the simulator were larger. The result for the slalom manoeuvre could also be improved by the introduction of a turn coordination system. A fair amount of pedal was required whilst turning because the control law provided a rate command response type in yaw. The purpose of the trial, however, was primarily to investigate the pitch control law, which included a nonlinearity in order to fix the speed of the response. The speed of the response was set to 15 deg/s. The pilot commented that a constant speed of response was pleasant because it made the aircraft behaviour in pitch very predictable. Based on this simulation, it seemed that a 10 deg/s speed of response would be fast enough for the MTEs considered. The conclusion from this trial was that FCL001 had reached a mature enough state to be tested in real flight. This is described in section 6.

The inner loop of FCL002 was designed earlier on in the project and successfully subjected to a limited piloted simulator trial in December 2005. After this, it was flight tested as part of a systems check at the NRC Canada. It was decided therefore that a nonlinear element could be added to this control law without additional piloted simulation.

6 FLIGHT TEST OF THE CONTROL LAWS

In late June 2006, two flight tests were performed on the NRC Bell 412 ASRA (see figure 6.1) during which each of the control laws was tested and data were recorded corresponding to step inputs of various sizes and frequency sweeps. The results obtained from the flight test of FCL001 are presented in the next paragraph, followed by the results of FCL002.

Figure 6.1: Flight test with the Bell 412 ASRA at the NRC

6.1 Flight test of FCL001

This control law was tested at approximately 20 knots, which is close to the design condition of 10 knots. Upon engagement it was found that the control law was stable. Several inputs in the pitch axis are presented in figure 6.1.

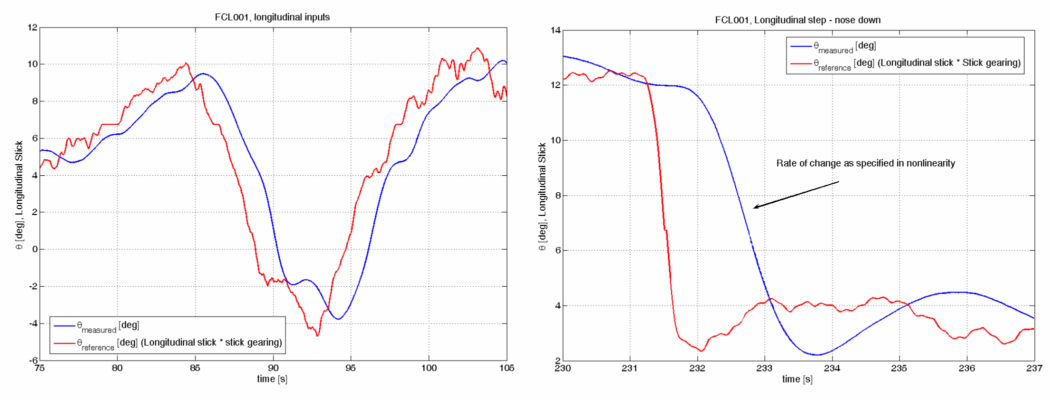

Figure 6.1: Longitudinal inputs with FCL001

The response type in pitch is clearly attitude command attitude hold. From the 'nose-down' step input on the right, it can be determined that the nonlinear element is functioning as intended. It was defined in this element that the rate of change in pitch attitude should be 10 deg/s when the pilot demands a 'large' change in pitch attitude. The pitch axis was perceived to be sluggish and the test pilot indicated that high-gain tasks in pitch would be difficult to perform due to a low bandwidth. The performance of the pitch control law had been set fairly low deliberately. Several inputs were also given in the other axes, results of which are displayed in figure 6.2.

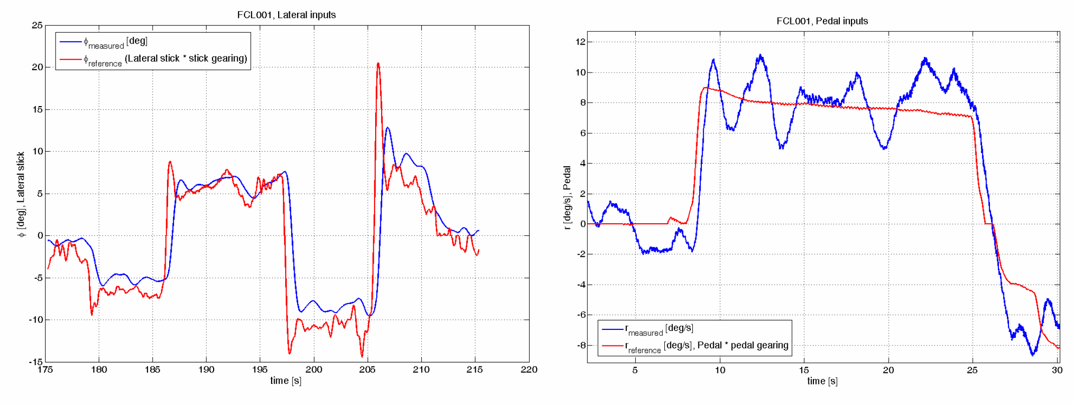

Figure 6.2: Lateral and pedal inputs with FCL001

The response type is clearly ACAH in roll and rate command in yaw. The pilot described the roll axis response as being crisp. From the figure it is obvious that the yaw rate tracks the reference signal coming from the pedal position, however it is evident that there are significant variations of the yaw rate about the reference signal. The pilot noted these variations as well. This is likely a result of the under-damped engine governor dynamics that produce torque oscillations at this frequency interacting with the control law or it can possibly be excited by gusts. In future work, gains will be tuned and a higher performance will be sought. Besides step inputs, several frequency-sweeps were performed in order to determine the bandwidth of the control law in the roll and pitch axes. The bandwidths from the flight test and from the calculations made on the 28-state linear model at the same flight condition are summarised in table 6.1.

Axis	ω_{BW} [rad/s]	τ_p [sec]	Handling Quality	
			Combat	Other
Pitch, predicted	1.6	0.21	2	1
Pitch, flight test	1.8	0.37	3	1
Roll, predicted	3.7	0.064	1	1
Roll, flight test	3.8	0.12	1	1

Table 6.1: Bandwidths from flight test and from calculation on the 28-state linear model at 20 knots

The predicted and actual bandwidths are close, which implies that the 28-state linear model is accurate enough for bandwidth predictions. The pitch bandwidth from flight test is slightly higher than the prediction. This may be due to the fact that the pilot inputs in the flight test occasionally entered the nonlinear regime of the controller, which made the gain of the outer loop increase and thereby the bandwidth as well. The phase delay is under-predicted for both cases.

6.2 Flight test of FCL002

The flight test of FCL002 consisted of two phases. The inner loop (i.e. without the nonlinearity) was first tested in December 2005. That test was just to establish that the C-code implementation worked and that the controller was flyable. Responses to longitudinal and lateral inputs with linear H-infinity inner loop controllers are displayed in figure 6.3.

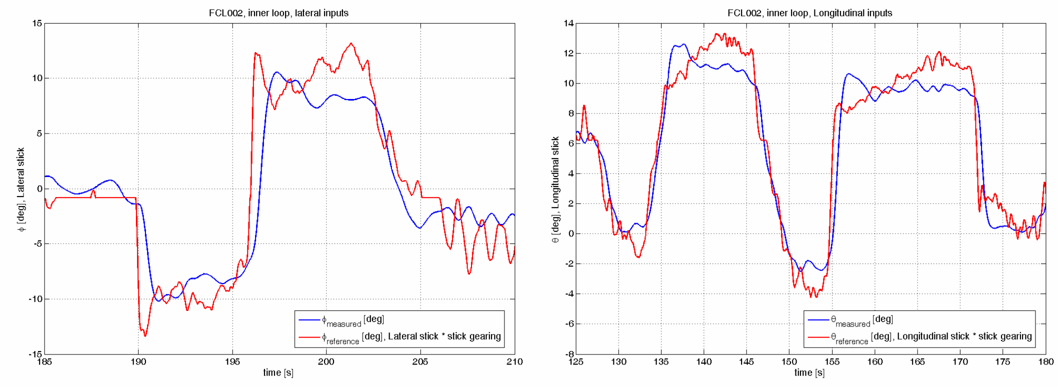

Figure 6.3: Longitudinal and lateral inputs with the inner loop of FCL002

The response type is ACAH in pitch and roll as designed and the reference signal is tracked well. Frequency sweeps in the pitch axis and roll axis were also performed with the inner loop of FCL002 at a forward flight speed of 20 knots. The roll axis bandwidth was found to be 4.1 rad/s and the pitch axis bandwidth 3.0 rad/s. These bandwidths correlate very closely to the predicted bandwidths of 4.2 rad/s and 3.1 rad/s, which were calculated on the 28-state linear model. This reinforces the point made earlier that for bandwidth predictions, the 28-state linearizations from the FLIGHTLAB Bell 412 model seem to be reliable.

Responses to lateral and pedal inputs obtained from the flight test of the complete control law including the nonlinear outer loop are presented in figure 6.4.

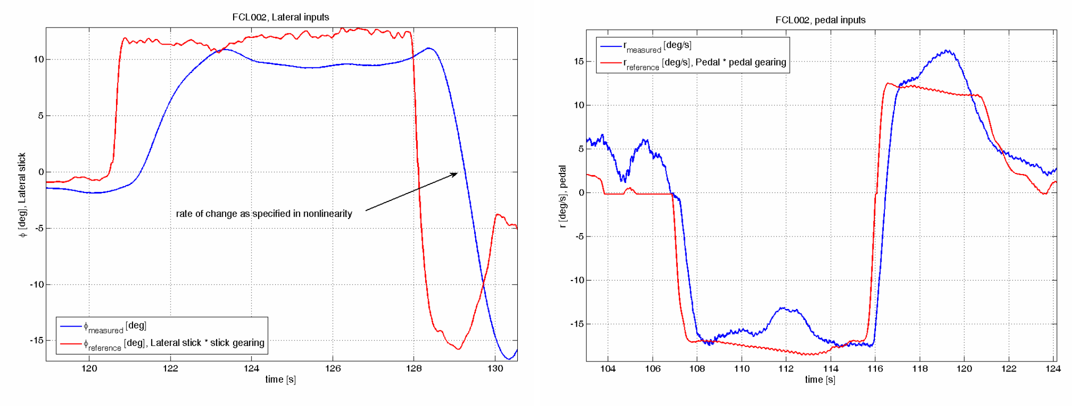

Figure 6.4: Lateral and pedal inputs with FCL002

A large lateral input is given at around t = 128 seconds, the speed of the response following this input is approximately 25 deg/s, which is as specified in the nonlinearity. This indicates that the scheme functions properly. The response following a pedal input indicates that the yaw rate tracks the reference signal. This concludes the evaluation of FCL002.

7 CONCLUSIONS AND RECOMMENDATIONS

Classical nonlinear control theory has been used in the design of two ACAH flight control systems for the Bell 412 Advanced Systems Research Aircraft. The method presented makes it possible for the designer to specify the speed of response of the system and thus the quickness. Flight control law FCL001 consists of a classical controller with a nonlinear outer loop. FCL002 on the other hand consists of linear controller designed with the H_∞ loop shaping design procedure in combination with a nonlinear outer loop. A high performance version of FCL001 was tested in a piloted simulator trial. Comments from the pilot indicated that this control law structure gives a pleasant, predictable response. Not only does the pilot know what attitude is commanded but also knows the rate at which it will be achieved. The performance specified via the nonlinear elements of both control laws was relatively low for the flight test, because the purpose of the first flight test was to prove the concept. The controllers all provided the specified characteristics and response types and were stable and flyable. The bandwidths achieved in flight matched the bandwidths predicted using the model developed during the same the project. By these measures, this flight test can be regarded as an important milestone. Our work on this and similar control schemes, combing modern robust control and practical, classical non-linear methods; with the aim of improving rotorcraft design is on going.

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