Simulation of automatic helicopter deck landings using nature inspired flight control and flight envelope protection

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ABSTRACT

The landing of a helicopter on a ship is one of the most dangerous of all helicopter flight operations. The Bell 412 advanced systems research aircraft is subject to a torque oscillation issue which increases pilot workload significantly when operating with low power margins and/or whilst performing tasks that require accurate torque control. This makes the deck landing task with this helicopter even more difficult. An automatic deck landing system was therefore developed. This system makes use of a novel control strategy for vertical control based on optical flow theory. Furthermore, it incorporates a torque envelope protection system. A successful automatic landing was performed in the flight simulator at the University of Liverpool. The novel control strategy created a very natural motion of the helicopter, similar to how a real pilot would fly it. The same control technique was subsequently applied to the simulation of an automatic lateral repositioning of a UH60 like helicopter in order to prove the generality of the technique. This manoeuvre was simulated successfully within level 1 handling qualities boundaries.

NOMENCLATURE

a_{1s}, b_{1s}	Lateral and longitudinal cyclic pitch [deg]
k	Variable describing profile of motion [-]
k_1, k_2	Gains in engine model [N, m]
p, q, r	Angular rates in aircraft body axes [deg/s]
Q_e	Engine torque [Nm]
t	Time [s]
T	Total duration time of motion [s]
x, y, z	Position [m]
w_f	Fuel flow [N/s]

Greek notation

ϕ, θ, ψ	Attitude in aircraft body axes [deg]

θ_0, $\theta_{0,tr}$	Main rotor and tail rotor collective pitch [deg]
χ	Gap [m, deg, N, etc.]
τ	Time to close a gap [s]
τ_1, τ_2, τ_3	Engine time constants [s]
Ω	Rotor speed [%]
X	State [m, deg, etc.]

Subscripts

ref	Reference
measured	Measured value

Abbreviations

ACAH	Attitude Command Attitude Hold
ASRA	Advanced Systems Research Aircraft
DVE	Degraded Visual Environment
FTM	Flight Test Manoeuvre
GVE	Good Visual Environment
HQ	Handling Qualities
HELI-ACT	Helicopter Active Control Technology
MTE	Mission Task Element
RC	Rate Command
RCDH	Rate Command Direction Hold
TRC	Translational Rate Command
WOD	Wind Over Deck

1. INTRODUCTION

The monitoring of rotorcraft structural, aerodynamic or control limits can impose a severe workload on the pilot and it can thereby significantly degrade handling qualities. It can therefore be very useful to provide an envelope protection system, such that the pilot does not have to monitor the limits anymore and can focus on his or her main task. This is commonly referred to as Carefree Handling (CFH), which is defined as the ability of a pilot to fly throughout an aircraft's operational flight envelope without concern for exceeding structural, aerodynamic or control limits (Loy 1997).

The Bell 412HP Advanced Systems Research Aircraft (Fig. 1) of the National Research Council (NRC) of Canada is subject to a torque oscillation issue. The engine torque of this aircraft exhibits an under-damped second order like dynamic response. This was determined after flight-testing the aircraft by the Flight Research Laboratory, of the Institute for Aerospace Research (IAR) of the NRC (Ellis and Gubbels 2001). The mast torque, closely related to the engine torque is not allowed to exceed certain limits. The pilot will therefore have to monitor these limits closely whilst performing manoeuvres where torque oscillations occur. This can cause a large increase in workload for the pilot. Unless this issue is addressed, it may comprise the handling qualities of advanced control laws, being tested on the ASRA, especially when operating with low power margins and/or whilst performing tasks that require accurate torque control. One such task is the landing of a helicopter on a ship. A pilot will then have to deal with (1) an invisible ship air wake, (2) poor visible cueing and (3) a landing spot which is moving up and down, rolling, pitching and yawing. The landing of a helicopter on a ship is therefore arguably one of the most dangerous of all helicopter flight operations (Padfield and Wilkinson 1997; Padfield 1998; Lee, Horn et al. 2003; Lee and Horn 2005).

In short, landing a Bell 412 on a ship deck is most likely a very difficult task with a high workload. It is therefore hypothesised that a flight control system, that can perform this

task for the pilot, would be very useful. Various studies have indicated that a fundamental optical flow parameter, called tau, is used in nature, both by humans and animals, for the guidance of motion. If such a parameter is used by a flight control system for the guidance of motion of a helicopter, then this might result in a flight control system that generates a natural movement, similar to what a normal pilot would try to achieve. Research performed at Liverpool University on optical flow theory in low-level helicopter flight and fixed wing approach and landing (Jump and Padfield 2005; Padfield, et al. 2007 and Padfield, Lee et al. 2001) has already shown that pilots use the so-called 'τ-coupling' in flight control. Besides performing automatic deck landings, the flight control system should be able to provide torque envelope protection throughout the manoeuvre.

The first aim of this paper is the development of a control system that is capable of performing automatic deck landings with the Bell 412 ASRA whilst providing torque envelope protection. A novel control strategy based on optical flow theory will be used to achieve this. The purpose of this is to make the landing system behave in a natural way, similar to an actual pilot. The second aim is to apply the same control technique on a different helicopter for a different task in order to prove the generality of the control technique. The FLIGHTLAB Generic Rotorcraft, a nonlinear helicopter model similar to the UH-60 Black Hawk is chosen for this. An automatic control system will be designed that performs the lateral repositioning mission task element (MTE) with this helicopter. The choice for this particular helicopter model and manoeuvre is quite arbitrary.



Figure 1.1: Bell 412 Advanced Systems Research Aircraft

The structure of this paper is as follows. Some basic theory on optical flow and the concept of nature inspired flight control is treated in Section 2. The two helicopter models which are used as test subjects to perform the research on are described in Section 3. Subsequently the design of a control law for the Bell 412 ASRA is discussed and the results of the simulation of an automatic deck landing are presented in Section 4. In Section 5, a control law for the FGR is presented and an automatic lateral repositioning manoeuvre is simulated. Finally, conclusions and recommendations are made.

2. NATURE INSPIRED AUTOMATIC FLIGHT CONTROL

2.1. Optical flow parameter tau

Much work has been performed in the field of ecological psychology on the theory of guidance of movement. Initially, Gibson suggested that pilots make use of information from the optical flow field when controlling an aircraft (Gibson 1998, original work 1958). Based on this work, Lee (1998) introduced the variable 'tau of a gap', which is defined as:

The time it would take the gap to close at the current closing rate.

The gap can be either spatial gap (such as distance, angle) or a force gap. The tau of a gap can also be written as an equation.

$$\tau_{\chi} = \frac{\chi}{\dot{\chi}} \qquad (2.1)$$

The tau of a gap is essentially the time it will take until the gap is reduced to zero at the current rate. In the context of this paper, spatial gaps are under investigation. Lee hypothesised that the tau of a motion gap is coupled to an intrinsic tau guide.

$$\tau_{\chi} = k\tau_{g} \qquad (2.2)$$

In which the intrinsic tau guide is a function of time (Lee 1998, Padfield, Lee and Bradley 2003)

$$\tau_{g} = \tfrac{1}{2}\left(t - \frac{T^{2}}{t}\right) \qquad (2.3)$$

Where T is the total duration time of the motion and k defines the profile of the motion (constant acceleration, acceleration – deceleration, etc.). Several studies have supported this hypothesis. Examples are: suction by newborn bottle-feeding, movement of the hand to mouth by adults when eating with the eyes closed, control of movement of the foot from one footfall to the next when sprinting, hand movements by a drummer (Lee 1998). Research performed at Liverpool University on optical flow theory in low-level helicopter flight and fixed wing approach and landing (Jump and Padfield 2005; Padfield, Clark et al. 2005 and Padfield, Lee et al. 2001) has indicated that pilots use the so-called tau coupling in flight control. The motion described by equations (2.1), (2.2) and (2.3) is visualized in figure 2.1.

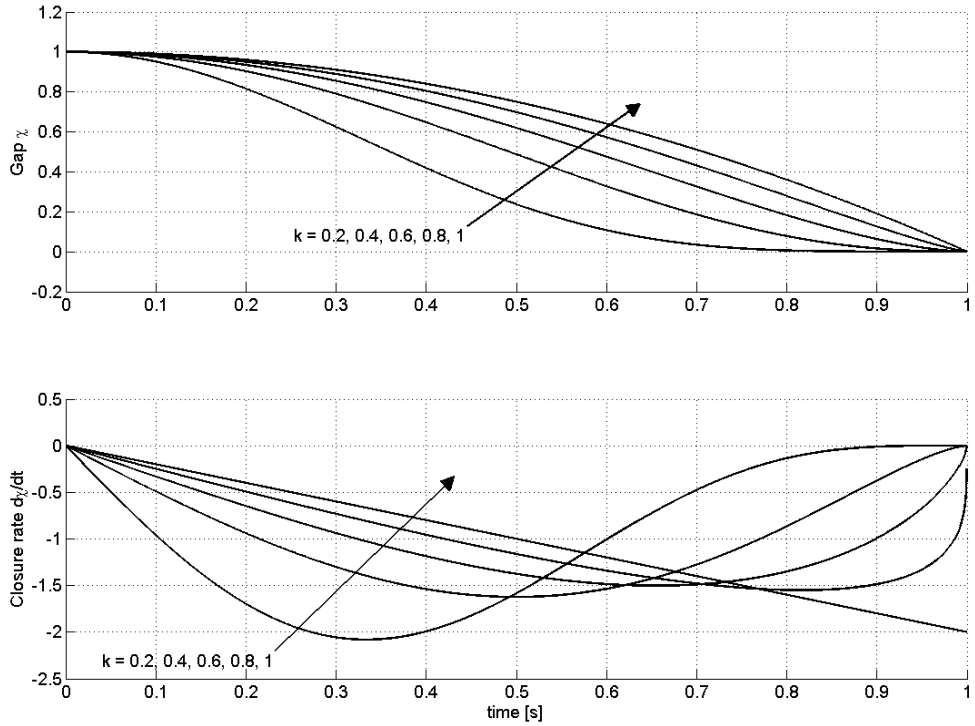


Figure 2.1: Closure of a gap χ described by tau theory for various values of *k*

It can be observed that the factor *k* influences the profile of the motion. For *k* equal to 1, the motion has a constant acceleration and there is a velocity present at the time that the gap is closed. For *k* equal to ½, the maximum velocity occurs exactly at ½*T* and the final velocity is equal to zero.

Later, a more general intrinsic tau guide was proposed (Rieser et al., 2005).

$$\tau_G = \frac{t\left(T+t\right)}{T+2t} \qquad (2.4)$$

This equation is also valid when the object starts with an initial velocity whilst the original equation is valid for an object starting without an initial velocity. It can be derived that equation (2.3) reduces to equation (2.4) when only the second half of the motion is considered (Jump and Padfield 2006).

In conclusion, it is likely that the variable tau is a fundamental parameter in nature and used by animals and humans for guidance of motion. In the context of helicopter flight control and based on this theory it would make sense to make use of this variable in automatic control systems of vehicles. A tau-based flight control strategy is therefore proposed in the next section

2.2. tau-based flight control

Equations (2.1), (2.2) and (2.3) can be combined to derive the next formula.

$$\dot{\chi} = \frac{2\chi}{k\left(t - \frac{T^2}{t}\right)} \qquad (2.5)$$

The variable χ in this equation can be interpreted as the error between a desired (reference) state X_{ref} and the current (measured) state $X_{measured}$, whilst the time derivative of χ can be seen as a reference signal for the time derivative of the state. Rewriting the equation then yields:

$$\dot{X}_{ref} = \frac{2\left(X_{ref} - X_{measured}\right)}{k\left(t - \frac{T^2}{t}\right)} \qquad (2.6)$$

This equation is essentially a proportional control system with a time dependent proportional gain. A schematic of this system is presented in figure 2.2.

Such a system is very generic and can be used in many different applications. For example it can be used to control a position (*x*, *y* or *z*) by generating a velocity reference signal. Of course a translational rate command system must be present then. It can also be used to control an attitude (ϕ, θ, ψ) by generating an angular rate reference signal (*p*, *q*, *r*). The variable *T* can be used to specify the time duration of the manoeuvre and can be seen as a measure for the aggressiveness. The variable *k* can be used to specify the profile of the manoeuvre. In the context of this paper, tau-control is only used for position control:

- Vertical position control during deck landing with a Bell 412 helicopter
- Lateral position control for the lateral reposition MTE with the FLIGHTLAB generic rotorcraft

The reader must bear in mind that tau-control can be applied to many more situations. The philosophy behind using optical flow theory as the basis of a flight control law is that it represents how a human pilot would actually perform the manoeuvre.

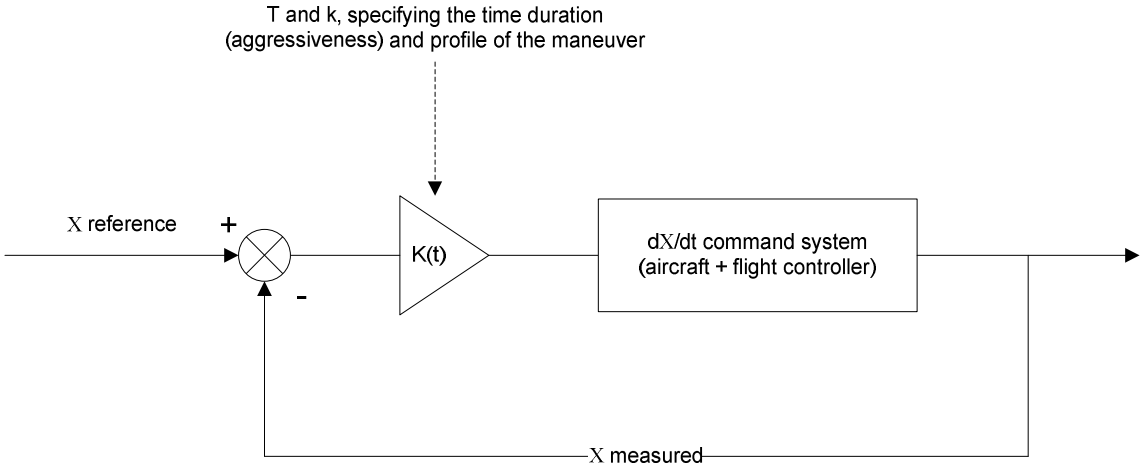


Figure 2.2: use of tau in feedback control system

3. HELICOPTER MODELS

3.1 Bell 412 Advanced Systems Research Aircraft

A high fidelity nonlinear simulation model of the Bell 412 ASRA has been developed within the HELI-ACT project (Manimala et al. 2007). The comprehensive real-time flight simulation software FLIGHTLAB (Du Val 2001) was used for this. The data required for the development of this model were partly acquired from literature in the public domain and partly by measurements performed on the ASRA at the NRC Canada. The model of the Bell 412 ASRA can be divided into several modules: (1) the rotor, (2) the tail rotor, (3) fuselage and aerodynamic surfaces, (4) the propulsion system and (5) the flight control system. There are some other modules present as well (e.g. atmospheric module), which are less relevant to the work presented here. The main rotor system is modelled as a blade element model with rigid blades, a Peters-He finite state inflow model (Peters and He 1995) and with quasi steady aerodynamics. Aerodynamic data for the airfoil sections are stored in two dimensional look-up tables. Sectional lift, drag and moment coefficients as a function of Mach number and angle of attack are stored in these tables. The tail rotor is modelled relatively simple as a Bailey rotor (Bailey 1941). The calculation of fuselage aerodynamic forces for helicopters is a very complex subject. There are two options in FLIGHTLAB to model the fuselage aerodynamics: a panel method and table look-up. The second option is chosen because sufficient information on this topic can be found in the public domain. Aerodynamic look-up tables were constructed from wind tunnel data of the Bell UH-1 airframe, published in references (Harris et al. 1979; Biggers, McCloud and Patterakis 1962 and Wilson and Mineck 1975). This airframe is similar to that of the Bell 412 helicopter. The aerodynamic surfaces (vertical fin and horizontal stabilizer) are modelled with two dimensional look-up tables. The horizontal surfaces have two special features. First, the left hand section of the elevator has a different incidence than the right hand section. These incidences were measured on the ASRA. Second, both sections are connected to a spring-loaded tube, which is attached to the structure of the tail boom. The pitch angle of the left-hand and right-hand elevator is a function of the moment caused by the torsional spring and the aerodynamic moment. It can therefore change dynamically during flight. The stiffness of the spring-loaded tube assembly was measured at the NRC.

Of particular interest to the research presented in this paper are the heave dynamics of the Bell 412 ASRA because tau-control will be used for vertical position control. The NRC has developed a state space model of the Bell 412 engine dynamics, based on system identification of flight test data (Hui, 1999). This model has 5 states and incorporates a time delay on the input. The states of the model are (1) required power turbine speed, (2) gas generator speed, (3) engine torque, (4) fuel flow rate and (5) commanded fuel flow rate from the differential pressure on the air regulator. The frequency domain software CIFER (Tischler and Caufman 1992) was used by the NRC to obtain this model. Both frequency sweeps and doublet inputs were used to acquire the flight

test data. The parameters in the state space matrices were obtained at three flight conditions; (1) Hover at sea level, (2) 60 knots forward flight at 3000 feet and (3) 60 knots forward flight at 8000 feet. The response of this model is a characteristic second order response similar to that of the real aircraft. The engine torque frequency response of the state space model matches the flight test data well and the bandwidth reaches 4 rad/s. The propulsion system in FLIGHTLAB is modelled as a 'simple engine model'. The simple engine model functions like an engine governor. It commands torque based on the difference between the current rotor speed and the rotor idle speed. The engine output torque is controlled by the governor system that senses a change in rotor speed ($\Delta\Omega$) and demands a fuel flow change (w_f). The fuel change is represented as a first order lag.

$$\tau_1 \dot{w}_f + w_f = k_1 \Delta\Omega \qquad (3.1)$$

where τ_1 and k_1 are the time constant and the gain, respectively. The gain k_1 can be chosen to give a certain prescribed droop in rotor speed from flight idle to maximum contingency fuel flow. The engine torque (Q_e) response to the fuel flow change is described by a lag responding to fuel flow and flow rate.

$$\tau_3 \dot{Q}_e + Q_e = k_2(\tau_2 \dot{w}_f + w_f) \qquad (3.2)$$

where k_2 is the gain and τ_2 and τ_3 are the time constants. Combining the above first order equations gives the second order equation:

$$\tau_1\tau_2 \ddot{Q}_e + (\tau_1 + \tau_3)\dot{Q}_e + Q_e = k_1 k_2[\Delta\Omega + \tau_2 \dot{\Omega}] \qquad (3.3)$$

The time constants and gains of the simple engine model were tuned to match the response of the NRC state space engine model in hover. A comparison of the model with flight test data following a collective '2-3-1-1' input is presented in Fig. 3.1 to give an impression of the model fidelity in the heave axis. The comparison in other axes is omitted from this paper. The interested reader can find a detailed analysis of them in Manimala et al. (2007). In general, the on-axis response of the helicopter model matches well with flight test data in all four axes. The off-axis response of the model matches less good (Manimala et al. 2007)

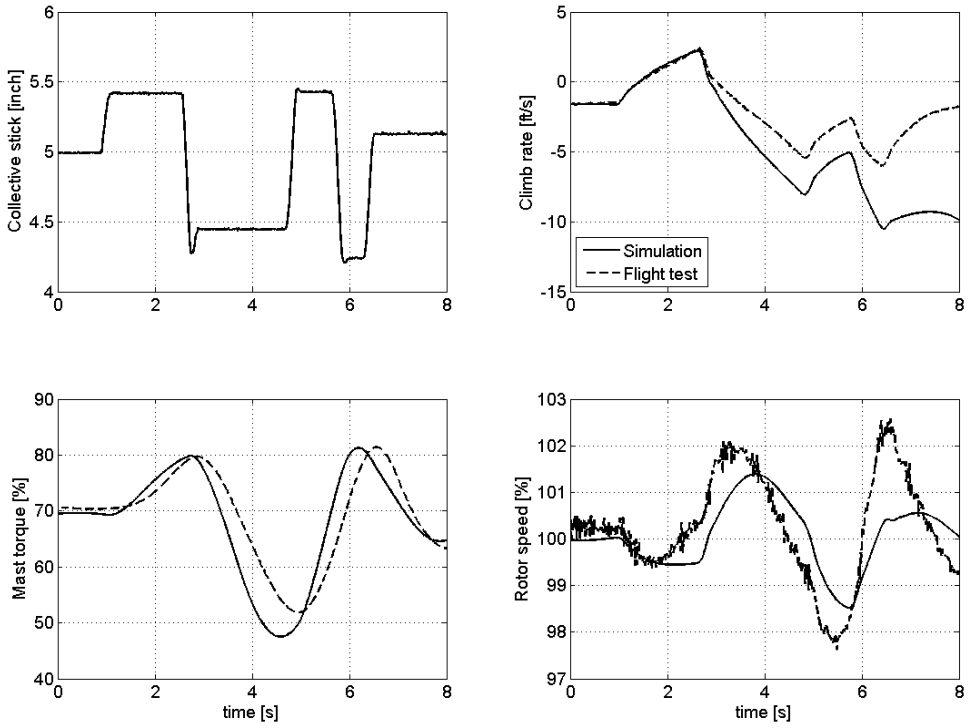


Figure 3.1: Comparison of the heave axis response of the nonlinear aircraft model with flight test data

The flight control system (FCS) of the bare airframe aircraft is a simple sequence of mechanical linkages and actuators, connecting the stick to the swashplate. The actuators are modelled as simple first order systems with a time constant of 1/60 s in combination with rate limiters. The rate limits are assumed to be 100 %/s of the total available actuator travel. This was assumed to be a reasonable representation of reality based on private communications with the NRC. It would be better to include higher order actuator dynamics. However, the knowledge required for this was not available. Modelling the higher order actuator dynamics is a recommendation for further work. The stick limits were measured on the ASRA, as well as the mechanical gearing ratios. From this it was possible to calculate the operational blade angle range. All of the above combined yields the following representation of the control system.

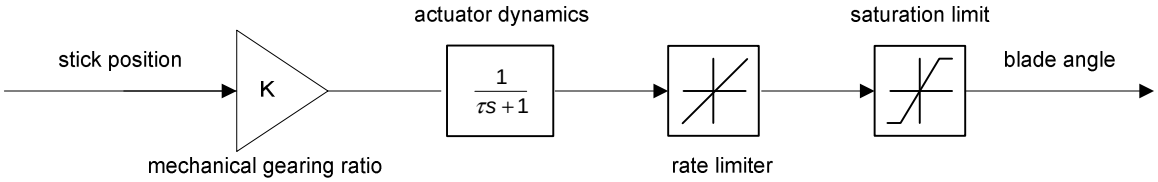


Fig. 3.2: The mechanical path from a stick deflection to a swashplate angle

Whenever a novel control law is implemented in this scheme, it will be introduced in the path between the actuator and the stick. This concludes the final module of the FLIGHTLAB Bell 412 model.

3.2 FLIGHTLAB Generic Rotorcraft

The FLIGHTLAB Generic Rotorcraft (FGR) simulation model is similar to the UH-60A Black Hawk helicopter. This model has a selective level of fidelity. The main modelling features of the FGR selected for the purpose of this paper are the following. The main rotor system is modelled as a rigid blade element model with a three-state inflow model and quasi-steady air loads. Aerodynamic data of the blades is stored in look-up tables as a function of the angle of attack, Mach number and Reynolds number. The aerodynamics of the fuselage, vertical tail and horizontal tail are also stored in look-up tables. The fuselage structure is modelled as rigid. A detailed dynamic model of the turboshaft engines and drive train is present as well. The tail rotor is modelled as a Bailey rotor (Bailey 1941). The flight control system consists of a mechanical flight control system (MFCS) in combination with a stability command augmentation system (SCAS). The SCAS is removed from the model because this allows the implementation of novel control laws and the evaluation of the bare airframe dynamic behaviour. The MFCS is modelled with (1) gains representing the gearing from the pilot inputs to the blade angles, (2) actuator dynamics, (3) actuator saturation limits and (4) actuator rate limits. The data required to model the MFCS are obtained from Howlett (1981).

4. AUTOMATIC DECK LANDING WITH THE BELL 412

4.1 Introduction

The aim is to automatically perform a deck landing with the nonlinear simulation model of the Bell 412 by using tau-control and flight envelope protection. The deck landing will be made on a type 23 Frigate of which a model is available at the University of Liverpool (Fig. 4.1).



Fig. 4.1: Simulator view of Type 23 Frigate

The requirements for this manoeuvre are defined in the deck landing MTE (Appendix A). Two additional requirements are also specified. First, the mast torque should be protected by the flight envelope protection system. Second, the vertical positioning during the manoeuvre should be performed in a natural way by using tau-control. The term natural is quite subjective and it will therefore be difficult to judge whether a manoeuvre is performed in a natural fashion. However, the flight profile can be compared to the gap closure profiles presented in Section 2 and a test-pilot can comment on the profile.

4.1 Control law

First a basic flight control law was developed providing an attitude command attitude hold (ACAH) response type in pitch and roll combined with a rate command response type in yaw. This controller was designed using classical techniques in combination with a nonlinear element in the pitch axis, which was used to specify the pitch attitude quickness. The basic flight control law was implemented on the Bell 412 ASRA and flight tested successfully. A detailed description and analysis of this control law is presented by Walker et al. (2007). The basic control law was used to develop a position command system combined with a heading command system. The control law structure for longitudinal and lateral position control is schematically represented in Fig. 4.2.

The *x* and *y* reference signal in this schematic are derived from the inertial x and y reference positions.

$$\begin{bmatrix} x_{ref} \\ y_{ref} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} x_{I,ref} \\ y_{I,ref} \end{bmatrix} \quad (3.4)$$

Heading control is achieved with a simple proportional control system by feeding back the heading angle. The error between the desired heading angle and the measured angle is multiplied with a proportional gain to create a yaw rate reference signal. This latter signal is limited to prevent yaw rates which are too high. The system is schematically represented in figure 4.3.

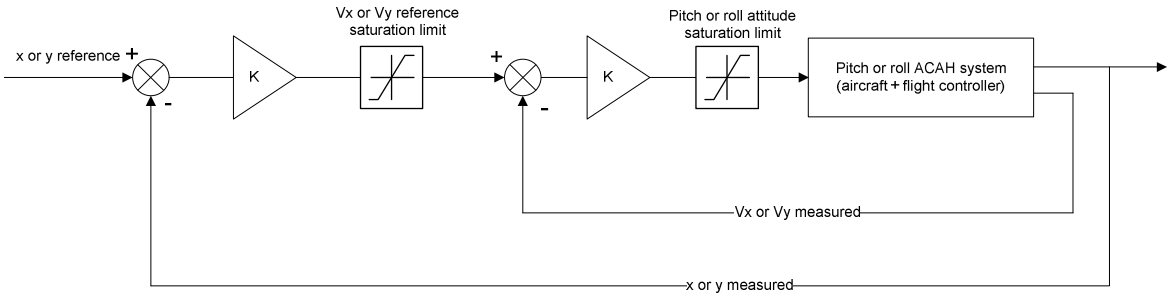


Fig. 4.2: Longitudinal and lateral position control

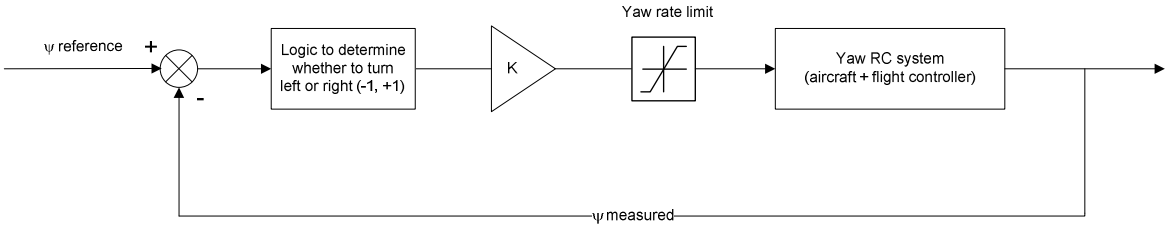


Fig. 4.3: Heading control

Note that there is a block with logic present in the loop that determines whether turning left or right is the shortest path to the desired heading angle. Although this system is used purely to track the heading angle in the research presented here, it could also function as the direction hold function in a rate command direction hold system (RCDH). This however would require some additional logic and nonlinear elements to determine if the pilot has the pedals in the middle position (i.e. zero yaw rate commanded).

The nature inspired flight control system and the flight envelope protection system are both implemented in the vertical axis. The basic control system for the vertical axis which creates a height rate command response type and with torque envelope protection is presented in figure 4.4.

One can see that this system consists of two loops. The inner loop is a torque control system which uses the measured torque as a feedback signal to demand a collective pitch angle. The torque controller was designed with the H-infinity loop shaping design method. The torque reference signal is created by the outer loop, which is simply a proportional controller. The torque reference signal is limited to the maximum transient torque limit. This heave axis controller was tested in the flight simulator at the University of Liverpool for the Bob-up MTE. Results in terms of Handling Qualities Ratings are presented in Fig. 4.5. A more detailed analysis of the control law, including nonlinear stability analysis can be found in Voskuijl (2007).

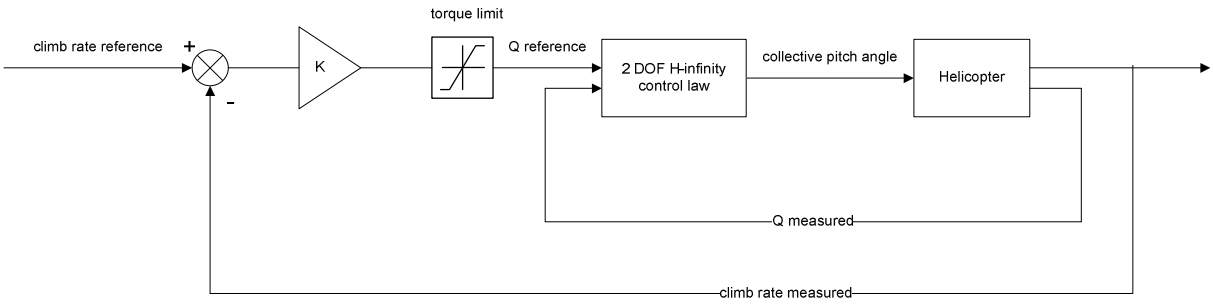


Fig. 4.4: Height rate control

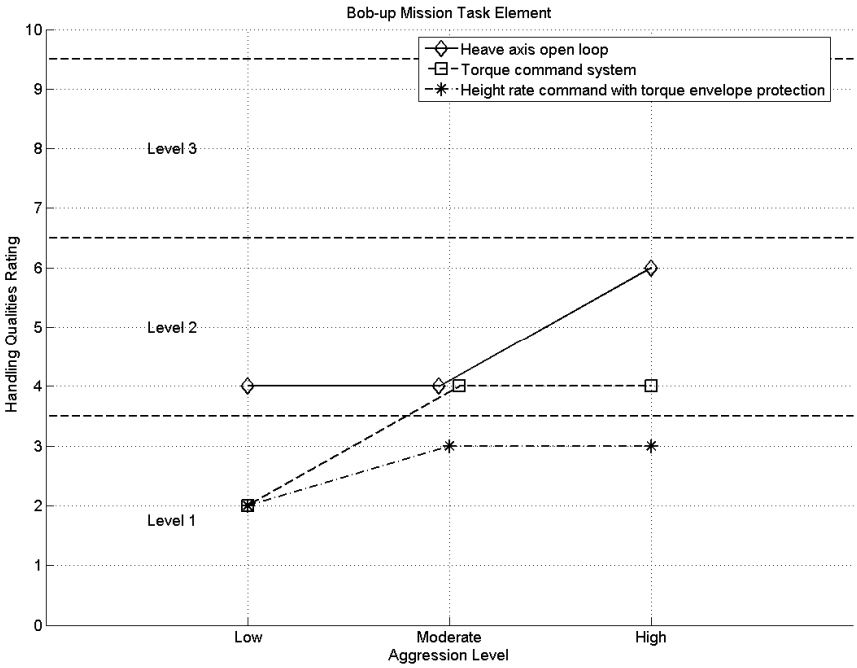


Fig. 4.5: Handling Qualities Ratings basic heave axis control law

The handling qualities ratings are improved from level two to level 1 for all levels of aggressiveness. Two factors played a major role in this result. First, the pilot did not have to monitor mast torque anymore due to the envelope protection system. This greatly reduced the workload. Second, the response type was changed to a height rate command system which made the control strategy more straightforward. Next, the tau-control system was applied to this basic control law to allow control over the altitude (Fig. 4.6). A saturation limit is introduced in the tau-control vertical positioning system to prevent large height rate commands.

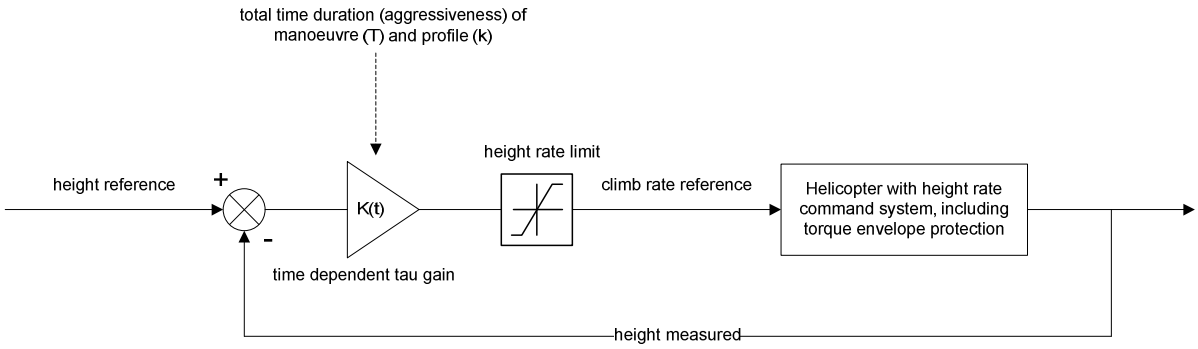


Fig. 4.6: Height control using tau theory

4.3 Results

The automatic landing system, described in the previous section, was tested in a real-time simulation in the flight simulator of the University of Liverpool. A test pilot was present in the simulator with the task merely to observe and comment on the behaviour of the system. The results of the test in terms of aircraft position, attitudes and velocities are displayed in figures 4.6 – 4.8.

The landing was successful within the desired limits of the deck landing MTE (Appendix A). The observing pilot commented that the final phase of the landing for which the tau flight control law was used appeared natural to him.

The three phases of the automatic deck landing can clearly be seen. The approach phase is initiated a few seconds after the start of the simulation. The aircraft pitches nose down to accelerate and nose up to decelerate. The desired *X* position in the inertial frame is successfully acquired and held. The 'sidestep' is then initiated at approximately 25 seconds which can be observed by an increase in the roll angle to the right. The desired position above the landing spot is achieved within approximately 10 seconds. Finally the landing with the nature inspired tau flight control law is initiated. The desired duration time *T* specified was 7 seconds and the factor *k* was set to 0.7. It was observed from several manual deck landings that these values are appropriate. The total duration time influences the maximum descent rate and the factor *k* set at 0.7 implies that there is a velocity at touch down.

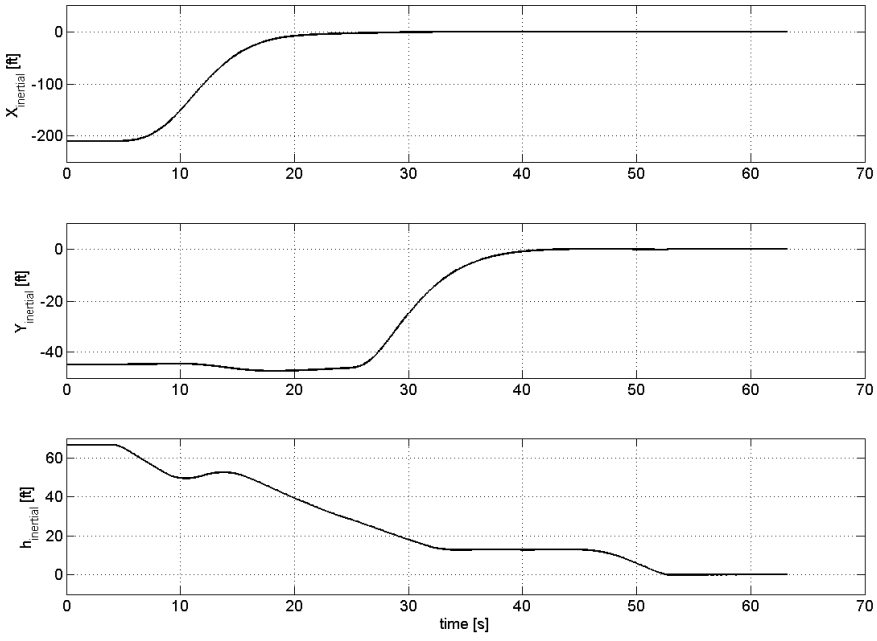


Fig. 4.6: Aircraft inertial position during the automatic shipboard landing

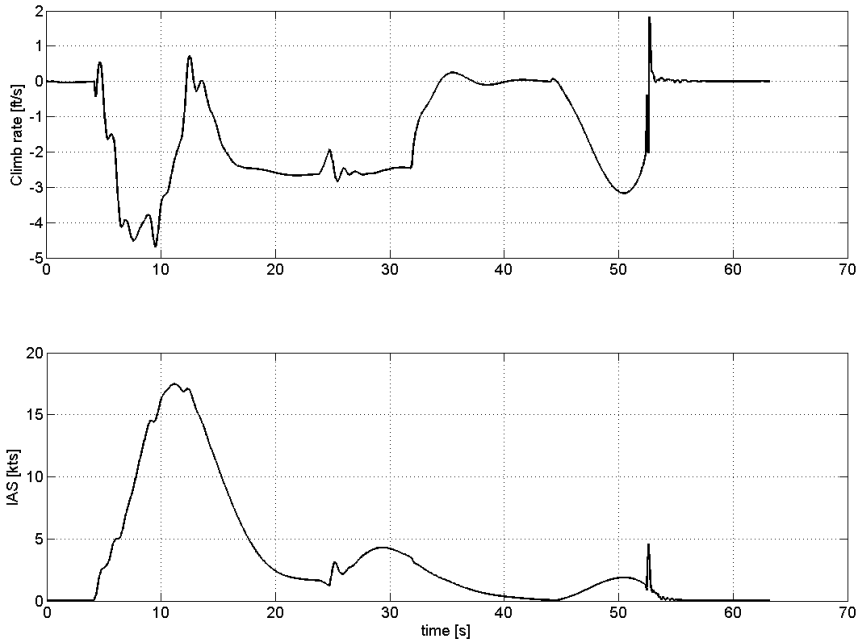


Fig. 4.7: Aircraft speed and climb rate during the automatic shipboard landing

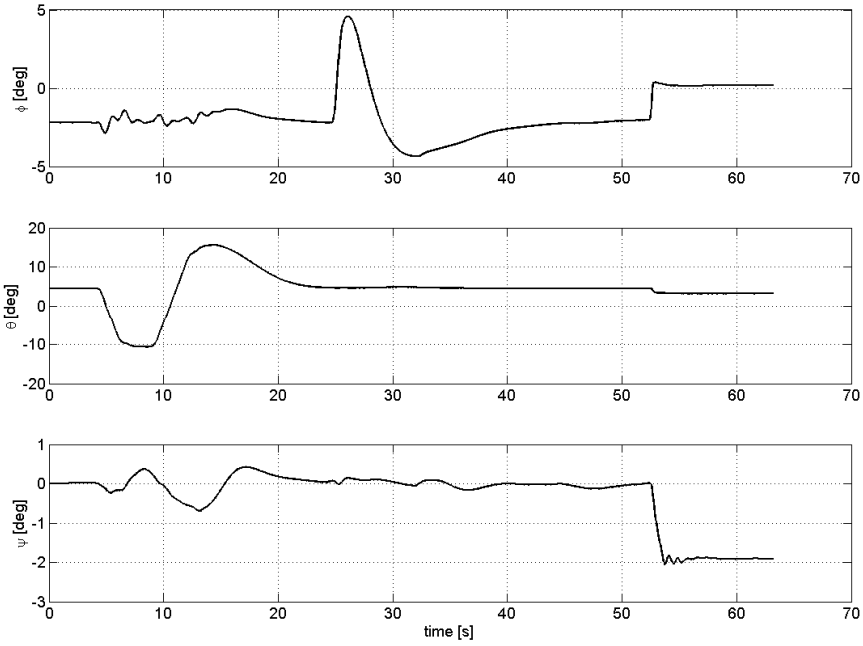


Fig. 4.8: Aircraft attitude during the automatic shipboard landing.

As soon as the landing gear contacted the deck, the collective pitch was lowered to its minimum value and all automatic flight control functions were disengaged. This is important because a ship deck can move and thereby determines the attitude of the helicopter. An active flight control law will try to counteract this.

In bad weather conditions, it is quite possible that the helicopter needs to be put on the deck rapidly. The aggressiveness and profile of the

landing can then be adjusted by varying the total time duration *T* and the factor *k*. It is a recommendation for future research to determine how the appropriate value of *T* varies as a function of the sea-state and possibly the type of ship on which the landing is performed.

The automatic deck landing presented in this paper is performed in good weather conditions without ship motion. It is a recommendation for further research to perform these automatic deck landings on a moving ship deck with an unsteady ship air wake present. Furthermore, in bad weather conditions, timing of the start of the vertical manoeuvre is essential. It will be beneficial to have an algorithm that predicts when a quiescent period will occur in which the landing can be performed safely. The development of this algorithm is a recommendation for future research as well. Finally, when control systems are developed, it is most important to prove their stability. This has not been done for the tau-control system which is essentially a linear time varying system. Stability analysis of the tau-control system is therefore also a topic of future work.

5. AUTOMATIC LATERAL REPOSITION WITH THE FGR

5.1 Introduction

The aim in this section is to achieve an automatic lateral repositioning with the FLIGHTLAB generic rotorcraft by using tau-control. The method is identical to the vertical position control of the Bell 412 during a deck landing as shown in the previous section. However, the controlled axis is different, as well as the helicopter type.

5.2 Control law

First a basic flight control law was developed, providing an ACAH response type in pitch and roll, an RC response type in yaw and a height rate command response type in the heave axis. A schematic of this system is presented in Fig 5.1.

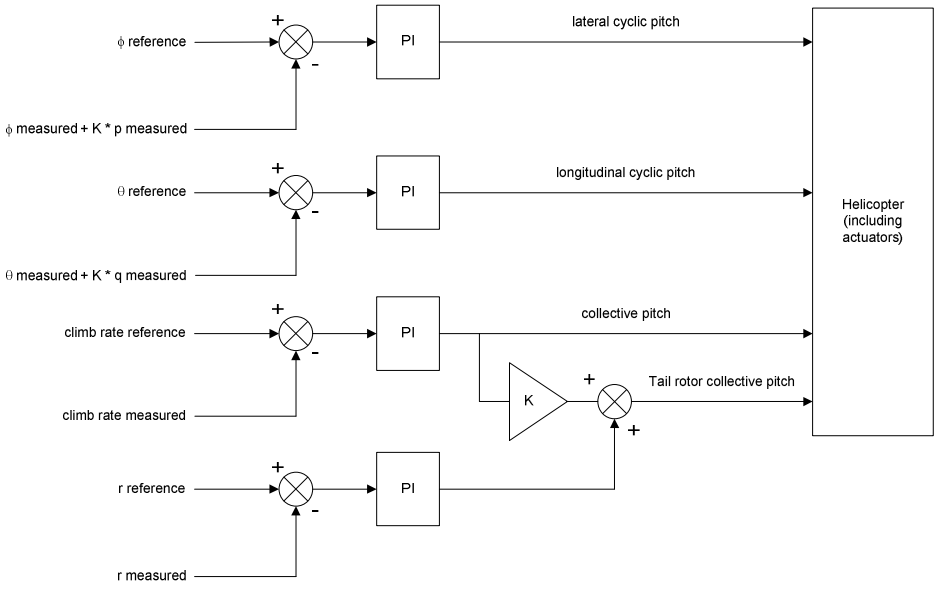


Fig. 5.1: Basic flight control law for the FLIGHTLAB generic rotorcraft

The system consists of four proportional plus integral (PI) controllers. The gains of these controllers were manually tuned with the aim to provide good handling qualities. Furthermore, it was decided to introduce a feed forward gain from the main rotor collective pitch demand signal to the tail rotor collective pitch angle in order to reduce the yaw due to collective cross coupling. The helicopter model used for the design was a high order linear model (41 states) derived from the nonlinear model in the hover condition. The resulting handling qualities, calculated via offline simulations are summarized in table 5.1.

All predicted handling qualities for non-combat manoeuvres are level 1 except for the yaw attitude quickness (level 2). A detailed analysis of this control law is omitted from this paper because the focus is on the tau-control system.

The basic control system was used as the core of an automatic positioning system. Outer loops were developed that provide lateral and longitudinal velocity control (TRC), a height hold and heading control. The tau control system was implemented on the lateral axis (Fig. 5.2).

ADS-33E-PRF requirement	***HQ level***
Inter-axis coupling	
Pitch due to roll for aggressive agility	1
Roll due to pitch for aggressive agility	1
Yaw due to collective for aggressive agility	1
Small amplitude changes	
Roll bandwidth for target acquisition and tracking	1
Roll bandwidth for all other MTEs	1
Pitch bandwidth for target acquisition and tracking	1
Pitch bandwidth for all other MTEs	1
Yaw bandwidth for target acquisition and tracking	2
Yaw bandwidth for all other MTEs	1
Moderate amplitude changes	
Roll attitude quickness for target acquisition and tracking	1
Roll attitude quickness for all other MTEs	1
Pitch attitude quickness for target acquisition and tracking	2
Pitch attitude quickness for all other MTEs	1
Yaw attitude quickness for target acquisition and tracking	3
Yaw attitude quickness for all other MTEs	2

Table 5.1: Predicted handling qualities of the basic flight control law for the FLIGHTLAB generic rotorcraft

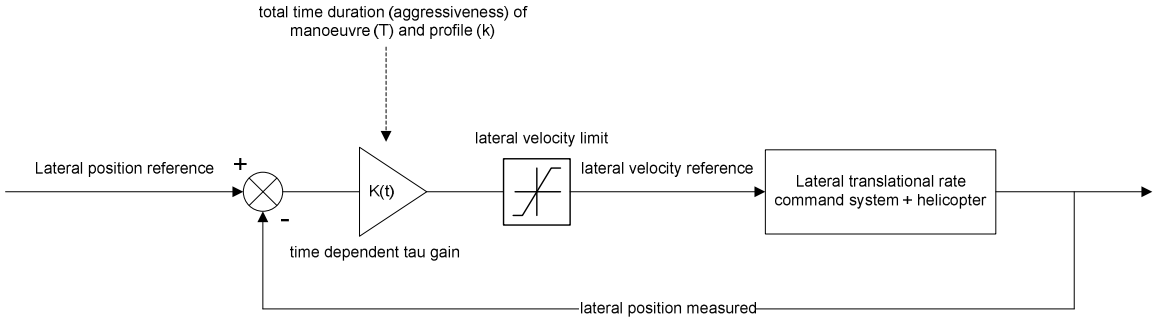


Fig. 5.2: Lateral position control using tau theory

5.3 Results

After the control law was designed, it was used to perform the lateral repositioning MTE (Appendix B) automatically. In short, this MTE prescribes that the rotorcraft has to reposition laterally over a distance of 400 ft within 18 seconds. The total duration time of the manoeuvre (variable *T* in the tau control law) was therefore set to 17 seconds to leave some margin for error. The factor *k*, describing the profile of the manoeuvre was set to ½. This means that the maximum velocity occurs exactly halfway during the manoeuvre and the final velocity is equal to zero. The lateral position of the aircraft is shown in Fig. 5.3. Clearly the lateral repositioning is performed within the desired limits. Furthermore, the profile of the manoeuvre seems natural. There is a smooth acceleration and deceleration and the final velocity is equal to zero. The longitudinal position and the altitude are presented in Fig. 5.4.

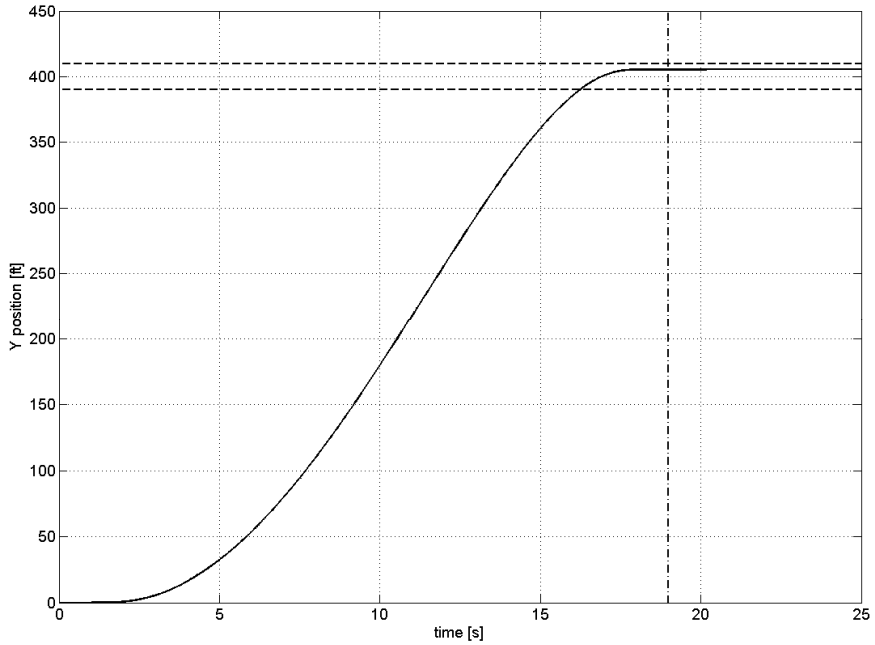


Fig. 5.3: Lateral position during automatic lateral repositioning manoeuvre

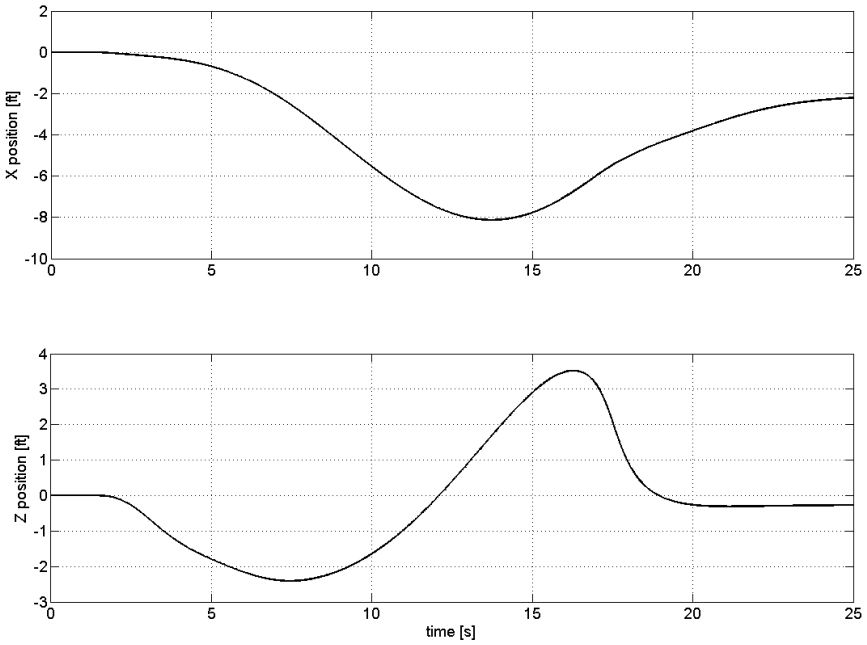


Fig. 5.4: Longitudinal position and altitude during automatic lateral repositioning manoeuvre

The longitudinal controller is a translational rate controller. In this case it tries to keep the velocity equal to zero. This is adequate to keep the longitudinal position within the desired (Level 1) limits. The vertical controller is a height hold system. Clearly the altitude is kept within the desired limits and the final altitude is approximately the same as the altitude at the start of the manoeuvre. Of course this is all achieved by rolling, pitching, yawing the helicopter. The aircraft attitudes are therefore presented in Fig. 5.5, which shows that the aircraft has to be banked approximately 10 degrees to the right to accelerate the aircraft and a roll angle of 25 degrees to the left is used to decelerate the aircraft. The pitch attitude deviation from trim remains quite small and the heading angle stays within the desired limits. Finally, the height rate remains within approximately $\pm$ 5 ft/s. The corresponding blade angles required to achieve the manoeuvre, are shown in Fig. 5.6. These angles are all sufficiently far from the actuator limits.

Overall, it can be concluded that the lateral repositioning MTE is performed successfully and the flight control law functions as desired. This verifies that tau flight control can be used not only for vertical control as shown in Section 4 but also for lateral control. In principle, the method is applicable to any rotorcraft type and to any ‘gap’ that needs to be closed. A nice feature of the system is that it does not need to be tuned. Only the total duration time and profile of the manoeuvre should be provided and then it will work.

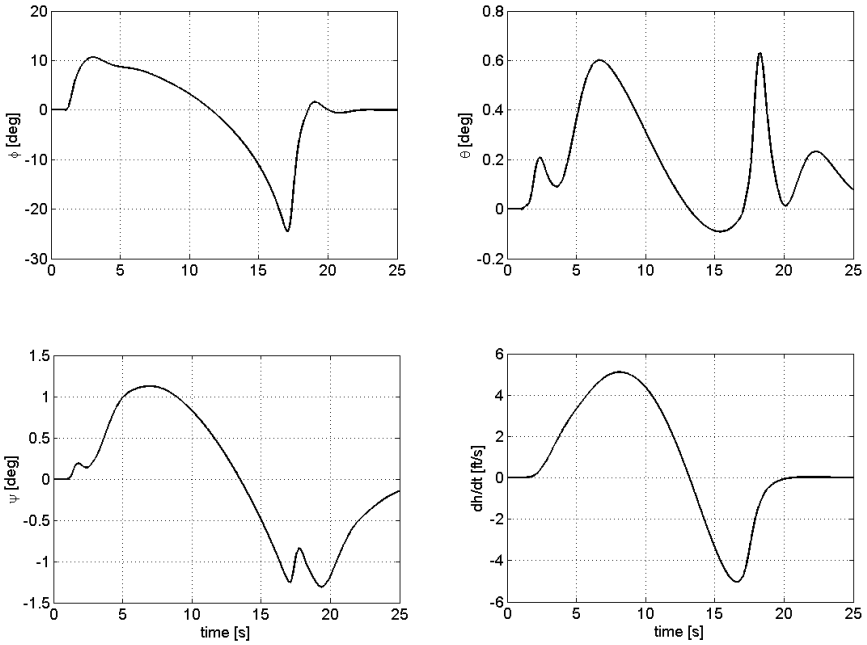


Fig. 5.5: Aircraft attitudes and height rate during manoeuvre (deviation from trim)

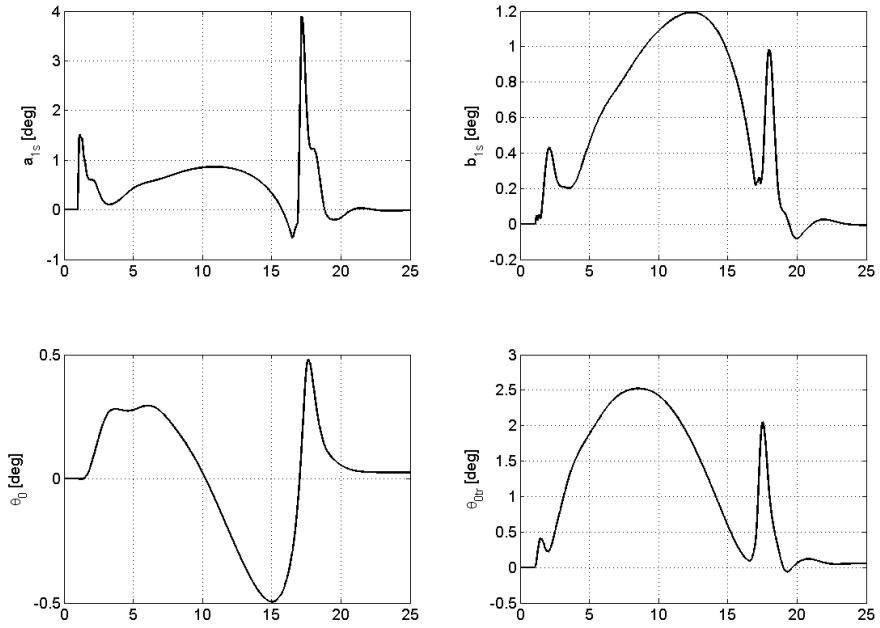


Fig. 5.6: blade angles during manoeuvre (deviation from trim)

One important question rises however. If such a system is implemented on a helicopter, then how should the pilot indicate to the flight controller what his or hers intentions are? It might be useful to use a three dimensional situation display in which the pilot can point (1) where to go, (2) the level of aggressiveness, and (3) the final velocity. It is even questionable if a pilot would really want such a flight controller in a helicopter.

However, this kind of control could be ideally suited to control the motion of unmanned aerial vehicles (UAV) from a remote control station. It could also be useful to drive an autopilot mode with the tau control technique such as a 'transition down/up mode', which is available on the AW101 maritime helicopter. A transition down is an automatic descent and deceleration from an entry point (e.g. 80kt, 200ft) to hover at a prescribed height (e.g. 40ft). Transition up is the other way. These are all suggestions and remain topics for further investigation.

6. CONCLUSIONS AND RECOMMENDATIONS

The first aim of this paper was the development of a control system, capable of performing automatic deck landings with a nonlinear simulation model of the Bell 412 ASRA, whilst providing torque envelope protection. The control system had to make use of optical flow theory in order to make the helicopter behave in a natural way, similar to an actual pilot. A control strategy was therefore developed based on optical flow theory. This strategy, designated as tau-control is applicable to many different situations. In principle it can be used to close any gap of interest, such as a position gap, an angular gap or a force gap. Tau-control requires only two parameters; (1) the aggressiveness of the manoeuvre and (2) the profile of the manoeuvre. There are no gains present that need to be tuned. However, it does require the system to be controlled to have a specific response type. In the context of this paper, tau-control is applied to the vertical position control of a Bell 412 helicopter. This implies that this helicopter should have a height rate command system present for the tau-control system to work. A translational rate command system was therefore developed, including a torque envelope protection system. An automatic deck landing was then simulated with the complete control system. Longitudinal and lateral position control was achieved with classical control techniques. Vertical position control was successfully achieved with tau-control and the observing pilot commented that the motion seemed natural to him. The second aim of this paper was to apply this technique to the lateral position control of a UH-60 like helicopter model in order to prove the general applicability of the technique. The lateral repositioning MTE was successfully performed within desired limits by using tau-control.

There are five recommendations for future research. First, a stability analysis of the tau-control system needs to be made. This is not a straightforward task because it is a linear time varying system. Second, since the automatic landing system will give most benefits in bad weather conditions, ship motion and an unsteady ship air wake need to be introduced. Third, an algorithm needs to be developed that can predict quiescent periods in ship motion during bad weather conditions. Fourth, an interface needs to be designed for the pilot to indicate his or her intentions to the tau-control system. As a suggestion, it might be useful to use a three dimensional situation display in which the pilot can point (1) where to go, (2) the level of aggressiveness, and (3) the final velocity. Finally, a tau-control system should be tested in-flight on the Bell 412 ASRA.

7. ACKNOWLEDGEMENTS

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APPENDIX A: DECK LANDING MISSION TASK ELEMENT

This mission task element is taken from Padfield (1998). The values of certain parameters such as touchdown velocity are adjusted to comply with the specifications of the Bell 412 helicopter (Anonymous 2002).

Objectives:

- Check control margins while manoeuvring over the flight deck and touching down within undercarriage limits for the full range of required WOD
- Check for sufficient agility to maintain position within the required standards while station keeping over the flight deck
- Check for undesirable cross couplings during a multi axis task
- Check performance of any control systems hold functions during the deck landing task
- Check for sufficiency of visual cues during lateral transition, station keeping and landing for the pilot to judge task performance
- Check for suitability of any ship-based or cockpit/helmet displays to guide the pilot during the deck landing task

Description of Manoeuvre:

From a stabilised hover off the port side of the ship, perform a lateral transition over the deck and position the aircraft above the landing spot. During this manoeuvre, the ship is likely to be rolling, pitching, yawing and heaving, to various extents depending on the ship speed and angle of attack relative to the waves and the WOD. Station keep over the landing spot within the required airborne scatter standards until the pilot judges that the ship motion is entering a quiescent period. The pilot should then descend and land with the deck lock grid between the aircraft's main wheels such that the securing harpoon can be engaged.

Description of Test Course:

For this FTM, there is generally no substitute for the actual or simulated ship. Land-based moving decks can be used provided the visual cues of the ship's superstructure and surrounding sea surface are sufficiently representative of the real world. The test course for the deck landing MTE is presented in Fig. A.1.

Desired performance

During the station keeping, maintain fore/aft position within an airborne scatter of 3m (±1.5m) and lateral position within an airborne scatter of 4.5m (±2.25m) relative to the deck lock grid. Heading variations should be less than ±5 deg. Torque excursions should not exceed maximum continuous torque. Height above the deck should be between 3m and 9m. During the landing, fore/aft positional accuracy would be within the fore/aft-landing scatter of 2.6m (±1.3m) and lateral landing scatter of 1.6m (±0.8m). Heading scatter should be within ±5 deg. Vertical velocity at touchdown should be less than 3.5m/s. Lateral velocity at touchdown should be less than 1.0m/s

Adequate performance

During the station keeping, maintain fore/aft position with an airborne scatter of 4.5m (±2.25m) relative to the deck lock grid and lateral position with a scatter of 6m (±3m). Heading variations should be less than ±10 deg. Torque excursions should not exceed maximum transient torque. Height above the deck should be between 3m and 12m. During the landing, fore/aft positional accuracy should be within the landing scatter of 2.6m (±1.3m) and lateral position within a 2.1m (±1.05m) scatter (size of deck lock grid). Heading scatter should be within ±10 deg. Vertical velocity at touchdown should be less than 4.2m/s. Lateral velocity should be less than 1.0m/s.

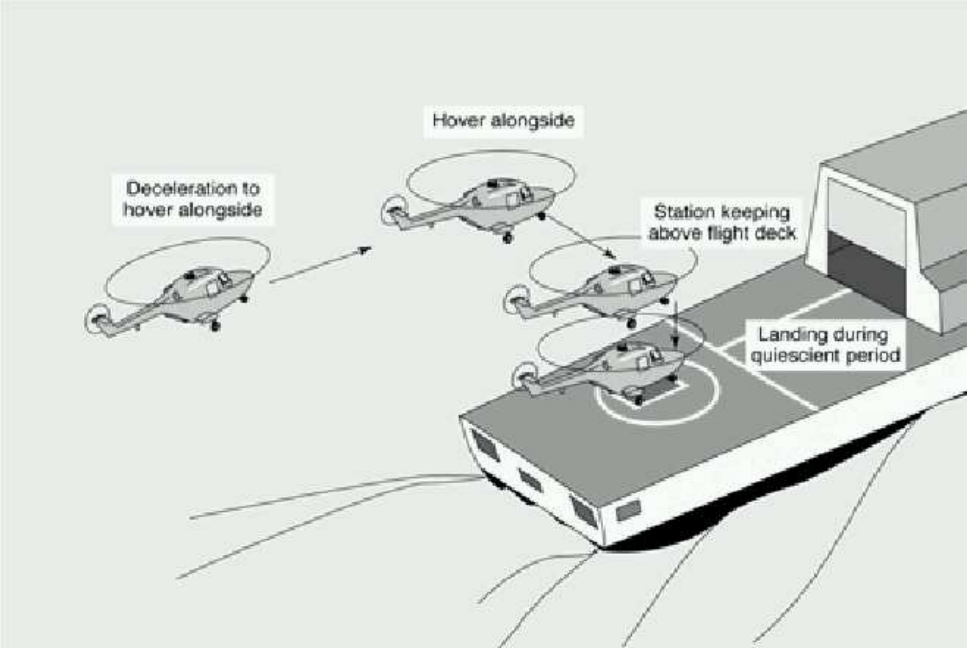


Fig. A.1: Deck landing mission task element test course (Padfield 2005)

APPENDIX B: LATERAL REPOSITION MISSION TASK ELEMENT

This mission task element is taken from ADS-33E-PRF (Anonymous 2000).

Objectives

- Check roll axis and heave axis handling qualities during moderately aggressive manoeuvring.
- Check for undesirable coupling between the roll controller and other axes.
- With an external load, check for dynamic problem resulting from external load configuration

Description of manoeuvre

Start in a stabilized hover at 35 ft wheel height with the longitudinal axis of the rotorcraft oriented 90 degrees to a reference line marked on the ground. Initiate a lateral acceleration to approximately 35 knots groundspeed followed by a deceleration to laterally reposition the rotorcraft in a stabilized hover 400 ft down the course within a specified time. The acceleration and deceleration phases shall be accomplished as single smooth manoeuvres. The rotorcraft must be brought to within +- 10 ft of the endpoint during the deceleration, terminating in a stable hover within this band. Overshooting is permitted during the deceleration, but will show up as a time penalty when the pilot moves back within +- 10 ft of the endpoint. The manoeuvre is complete when a stabilized hover is achieved.

Description of test course

The test course shall consist of any reference lines or markers to denote the starting and endpoint of the maneuver. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance.

Performance standards

	Cargo / Utility		Externally slung load	
	GVE	DVE	GVE	DVE
Desired performance				
Maintain longitudinal track within +- X ft	10	10	10	10
Maintain altitude within +- X ft	10	10	10	10
Maintain heading within +- X deg	10	10	10	10
Time to complete maneuver	18	20	25	25
Adequate performance				
Maintain longitudinal track within +- X ft	20	20	20	20
Maintain altitude within +- X ft	15	15	15	15
Maintain heading within +- X deg	15	15	15	15
Time to complete manoeuvre	22	25	30	30