Comparing the Flight Dynamics Characteristics of Tandem and Conventional Helicopters for the Purposes of Automatic Control

Kevin Ferguson
Douglas Thomson
Dave Anderson
Murray Ireland

Aerospace Sciences Research Division
School of Engineering
University of Glasgow
Glasgow, United Kingdom

Ziming Tu
Slyvain Manso
Arvind Chandran
Gokhan Ibal

Defence Science and Technology Group
Department of Defence
Australia

ABSTRACT

The broad aim of the collaborative research programme between the Australian Defence Science Technology (DST) Group and the University of Glasgow has been to develop a simulation framework capable for use in operational research to analyse helicopter mission effectiveness. This has involved integrating flight mechanics models of the helicopter with radar, guidance, weapons and threat models to allow typical operational scenarios to be modelled within a simulation framework designated CHOPPA. One objective of this broad aim is to develop a control system for generic rotorcraft configurations to quantify mission effectiveness. This paper presents the recent activity between the University of Glasgow and the DST Group towards achieving this goal. The starting point for developing a control system is understanding the flight dynamics of the rotorcraft that is to be controlled. As the control system will be implemented in conventional and tandem helicopter simulations, it is important to identify and compare the flight dynamics characteristics between these two rotorcraft arrangements. Consequently, the paper presents the salient flight dynamics attributes of a tandem helicopter and a conventional helicopter. The tandem and conventional helicopters of interest are the CH-47 Chinook and the UH-60, respectively. The first part of the paper focuses on the flight mechanics of these vehicles and how a control system can be developed to improve the operational effectiveness of both rotorcraft configurations. Thereafter, the basic control structure of the autopilot is introduced. Subsequently, a case study of the autopilot using a CH-47 mathematical model is presented.

NOMENCLATURE

com	commands
e	error vector (various units)
p,q,r	angular rates in body axes (rad/s)
$\mathbf{r}$	reference vector (various units)
u,v,w	translational body velocities (ft/s)
$\mathbf{u}$	control vector (inch)
$\mathbf{u}^*$	inner loop control vector (inch)
v	sideslip velocity (ft/s)
$\mathbf{x}$	state vector (various units)
x_b, y_b, z_b	body axes
$\mathbf{y}$	output vector (various units)
$\dot{z}$	climb speed (ft/s)
I_{xx}	moment of inertia in the x-axis (kg.m^2)
$\mathbf{K}$	inner loop matrix (various units)
L_p	roll damping derivative (1/s)
M_q	pitch damping derivative (1/s)
M_w	angle of attack derivative (rad/s.m)
N_r	yaw damping derivative (1/s)
N_v	directional derivative (rad/s.m)
T_{front}, T_{rear}	thrust of the front and rear rotor (kN)
V_f	airspeed (ft/s)
Z_w	heave damping derivative (1/s)
χ	track angle (deg)
δ_c	collective control (inch)
δ_b	differential collective control (inch)
δ_s	lateral cyclic control (inch)
δ_r	differential lateral cyclic control (inch)
μ	real part of eigenvalue (1/s)
ω	frequency (rad/s)

Presented at the 41th European Rotorcraft Forum, Munich, Germany, September 1-4th, 2015.

1. INTRODUCTION

The broad aim of the collaborative research programme between the DST Group and the University of Glasgow has been to develop a simulation framework for analysing helicopter mission effectiveness. This has involved supplementing flight mechanics models of the helicopter with radar, guidance, weapons and threat models. The end result is a simulation framework, called CHOPPA, which is capable of modelling typical operational scenarios. The main aim of this paper is to report the recent activity in the University of Glasgow and DST Group collaboration in developing a generic autopilot control system for the purposes of Operations Research (OR). It is widely recognised that the helicopter requires some form of augmentation so that pilots can complete missions effectively and safely[1]. Therefore, including an autopilot system within CHOPPA will enhance the fidelity of the simulation results. The goal is to develop a generic autopilot system which can be tailored to be used on a variety of rotorcraft which are of interest to the DST Group. It is important to stress that the autopilot system will be used for the purposes of OR simulations and there are no plans to implement this system in the operational aircraft.

Modern helicopters are extremely complex systems and they are generally considered more difficult to model than a fixed wing aircraft in the simulation world. A 6 degree of freedom (DOF) flight model provides for a relatively accurate modelling of the motion and flying characteristics of a helicopter. The DST Group has developed both non-linearised and linearised 6 DOF helicopter models for many of the helicopters servicing the Australian Defence Force (ADF) in the past. With the ADF's acquisition of seven Chinook CH-47F helicopters to replace its ageing Chinook CH- 47D fleet, the DST Group is being tasked to develop new and more effective tactics to fight the enemy on the front line. As the simulation framework of CHOPPA models typical operational scenarios, it has proven to be useful to investigate the merits of various tactics and therefore is an effective modelling tool for OR purposes[2].

One important element of the CHOPPA framework is the level of helicopter modelling. Generally speaking, there are different levels of fidelities required in the OR world. It all depends upon what it is being studied. For example:

- **First level modelling** - simple performance calculation using the flight manual and/or data provided the manufacturer. It is often used in the OR acquisition project to select the best tender.
- **Second level modelling** - helicopter performance in campaign level simulation, where locations and speeds are major factors in the studies. Then the 3 DOF flight model should be applied. This means that the equations of motion only determine x, y and z displacements of the helicopter in space. The actual characteristics of the helicopter are based on the so-called "performance" equations, which themselves are usually only defined for steady-state situations.
- **Third level modelling** - OR analysts are often presented with questions similar to the following: When the helicopter is doing an evasive manoeuvre, how effective the counter measure will perform (flare/chaff ejection path changed due to the fuselage orientation)? Will the counter measure be a threat to the team mate in a formation fly? Will the sensors/weapons be out of gimbal's limits during the manoeuvre? These type of studies are mostly related to the close-air-support (CAS) missions or scenarios. It ultimately brings in the other performance characteristics, such as roll, pitch, yaw, angular accelerations, etc.

The DST Group's full non-linearised models are usually developed by its Aerospace Division and are generated in the FLIGHTLAB environment for engineering research or accident investigation purposes. The advantage of FLIGHTLAB is that high fidelity flight models can be developed quickly. However, it is computationally expensive, and it is difficult to integrate with the JOAD's CHOPPA environment. Therefore, a simplified linearised version of the 6DOF model equipped with an autopilot function is an ideal solution for the JOAD's Operations Research purposes. An additional benefit of the linear model is that it typically forms the basis of the control system design. The development of the new Chinook CH-47F linearised 6 DOF aerodynamics model, equipped with the autopilot function will give the DST Group an edge on its tactic development effort, especially for CAS missions.

The starting point of the design of any controller is to understand the mechanics of the vehicle. Due to the DST Group's interest in both tandem and conventional helicopters, this paper focuses on the CH-47 and UH-60 helicopters. The paper begins by introducing the CH-47 tandem helicopter, and subsequently discusses the CH-47 and UH-60 flight dynamics characteristics. These characteristics include the control, trim and dynamic stability of these two rotorcraft. Thereafter, the basic autopilot control system is presented with the stability results of the CH-47 and the UH-60 highlighting what functions the controller has to perform to stabilise the vehicle and provide guidance control. The final portion of the paper presents an example of the autopilot system controlling the CH-47B mathematical model.

2. CH-47 Tandem Helicopter

The Chinook CH-47, as shown in Figure 1, is a twin-engined tandem helicopter which is used primarily for transport missions. The vehicle features two rotors, which rotate in opposite directions with the front rotor rotating anti-clockwise whereas the rear rotor rotates clockwise, when viewed from above. One of the primary design benefits of the tandem helicopter is that the two rotors are capable of providing a significant lifting force. This situation does not occur in the conventional helicopter as the main rotor is the only source of lift. As a consequence, the tandem helicopter is able to carry significant payloads which is why it is almost exclusively used for transport missions. Although the number of tandem helicopters in service is not as large as the conventional helicopter, the tandem helicopter does occupy an important role in vertical flight aviation.

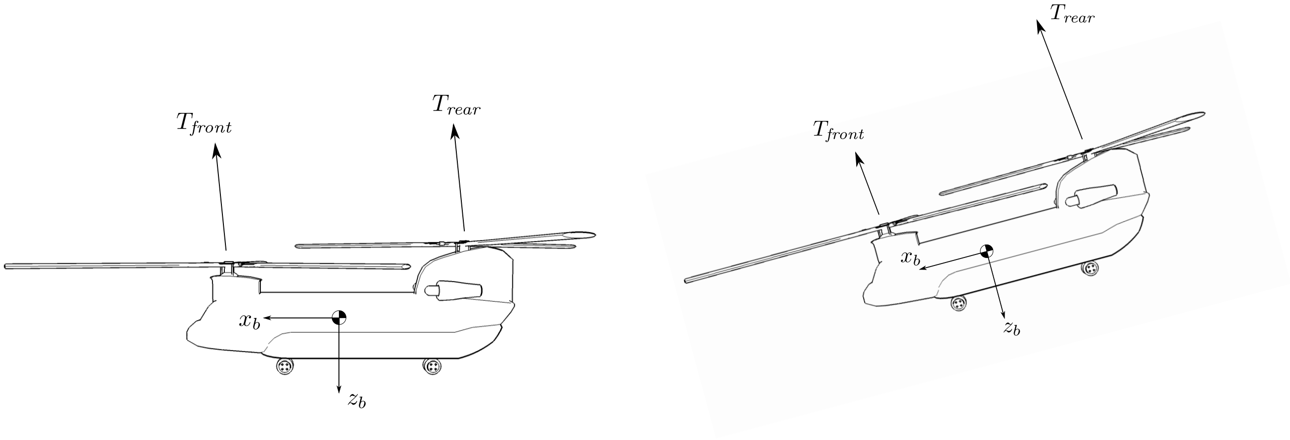
Due to the unique design of the CH-47 helicopter, its flight dynamics characteristics differ from that of the conventional helicopter in a variety of ways. One important difference between the two types of aircraft is how they are controlled. The control of the conventional helicopter is well understood and is explained in the standard helicopter textbooks[1,3–5]. The main rotor provides the lifting and propulsive forces whereas the tail-rotor, located at the rear of the aircraft, controls the yawing motion of the helicopter. Control of the conventional helicopter is achieved through the application of collective and cyclic control via the swashplate. The main rotor collective controls the vertical acceleration of the vehicle, whereas the application of cyclic pitch controls the tilt of the rotor thrust vector thereby allowing the aircraft to pitch and roll. The other important component of the conventional helicopter, the tail-rotor, creates a side-force which allows the aircraft to yaw.

Fig. 1. Australian CH-47D Helicopter

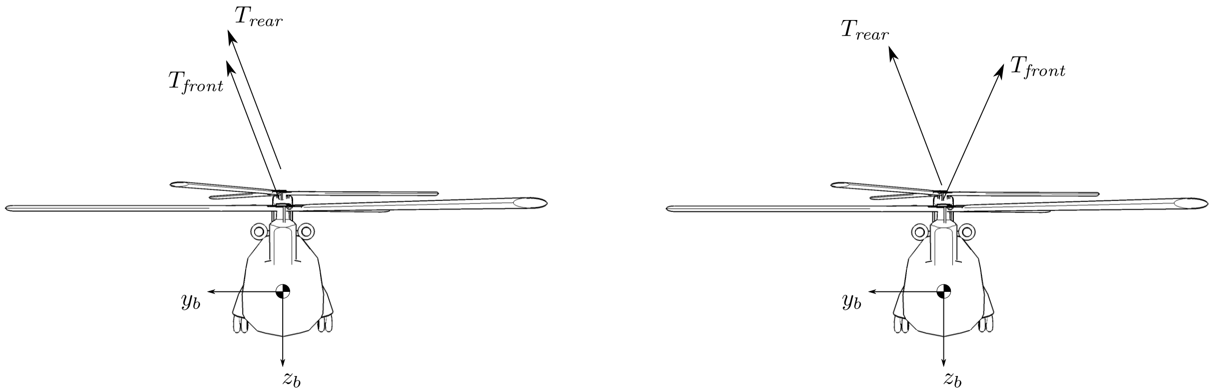
As mentioned previously, the control of the tandem helicopter is different from that of the conventional helicopter due to the aircraft's layout. Upon examining the tandem helicopter arrangement, Figure 1, there are some aircraft components missing when compared to the conventional helicopter. Firstly, there is no tail-rotor as the the front and rear rotors provide the yaw control. Secondly, there is no horizontal tailplane to provide a stabilising contribution to the pitch axis. Due to the arrangement of the front and rear rotors, it is impractical to mount a tailplane on the airframe[3]. Thirdly, there is no vertical fin on the aircraft although the rear pylon of the CH-47 does provide a small stabilising contribution to the vehicle's lateral modes[3]. These salient design features, as well as other factors, require an alternative method to control this type of aircraft class. Figure 2 presents the controls of the tandem helicopter. The application of the collective stick, denoted by δ_c, increases or decreases the blade pitch of the front and rear rotors by an equal amount. The net effect is that this control can increase or decrease the vertical acceleration of the tandem helicopter, as seen in Figure 2(a). Pitch control of the tandem helicopter is achieved through a differential collective control, δ_b. This is controlled by the pilot by moving the main stick forward or aft. A forward movement of the stick increases the pitch of the rear rotor's blades and has the opposite effect on the front rotor's blade pitch. The end result is that the thrust from the rear increases and there is a reduction of rotor thrust from the front rotor. Hence, the aircraft is able to pitch as seen in Figure 2(b). The lateral control of the tandem helicopter is controlled by displacing the main stick to the left or to the right. Moving the stick to the right tilts the front and rear rotors laterally to the starboard side of the helicopter, therefore increasing sideslip. This control is given by δ_s with the effect of the control demonstrated in Figure 2(c). The final control, δ_r, is called differential lateral cyclic and is used to control the yawing motion of the tandem helicopter, as seen in Figure 2(d). The application of δ_r increases the lateral cyclic of the front and rear rotors but in opposite directions. The front and rear rotors tilt laterally in different directions, Figure 2(d), thereby yawing the vehicle.

3. TRIM CHARACTERISTICS

Figure 3 compares the pilot controls of the CH-47B and UH-60 helicopters to maintain steady level flight. The controls for the CH-47B were obtained from an established data-set[6] whereas the UH-60 results were obtained from a FLIGHTLAB simulation. The trend of the two collective controls follow the standard bucket profile



(a) Collective Control, δ_c (b) Differential Collective, δ_b



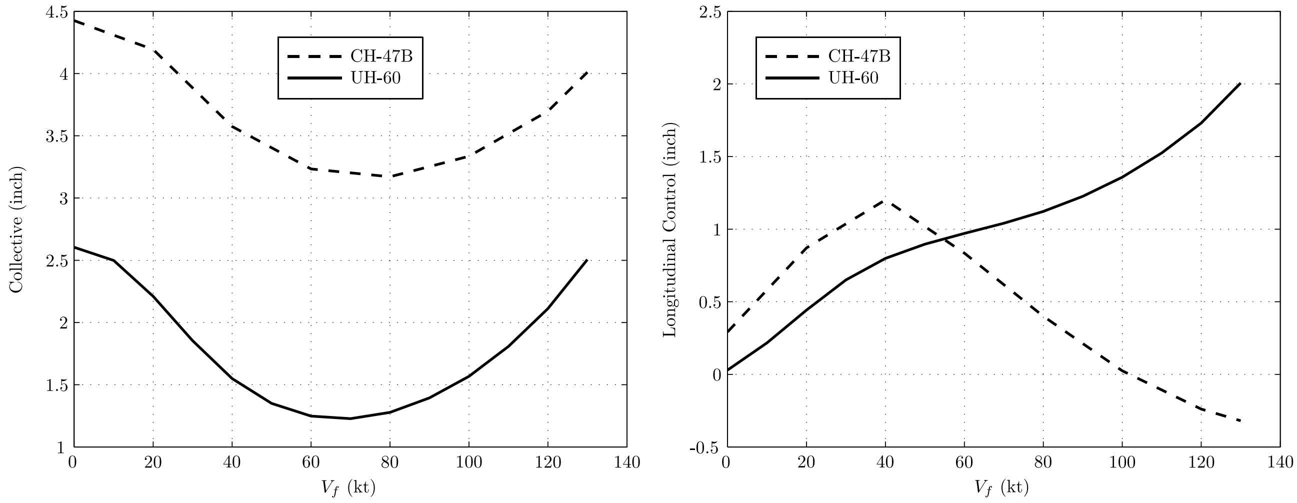
(c) Lateral Cyclic, δ_s (d) Differential Lateral Cyclic, δ_r

Fig. 2. Controls of a Tandem Helicopter

shape, Figure 3(a). As each of the aircraft move into forward flight, the required amount of collective reduces due to increase of dynamic pressure across the rotor blades. For each configuration, the minimum collective which is required to the trim the respective aircraft configuration is reached at approximately 70kt, before increasing to promote greater rotor thrust to overcome the rising airframe drag.

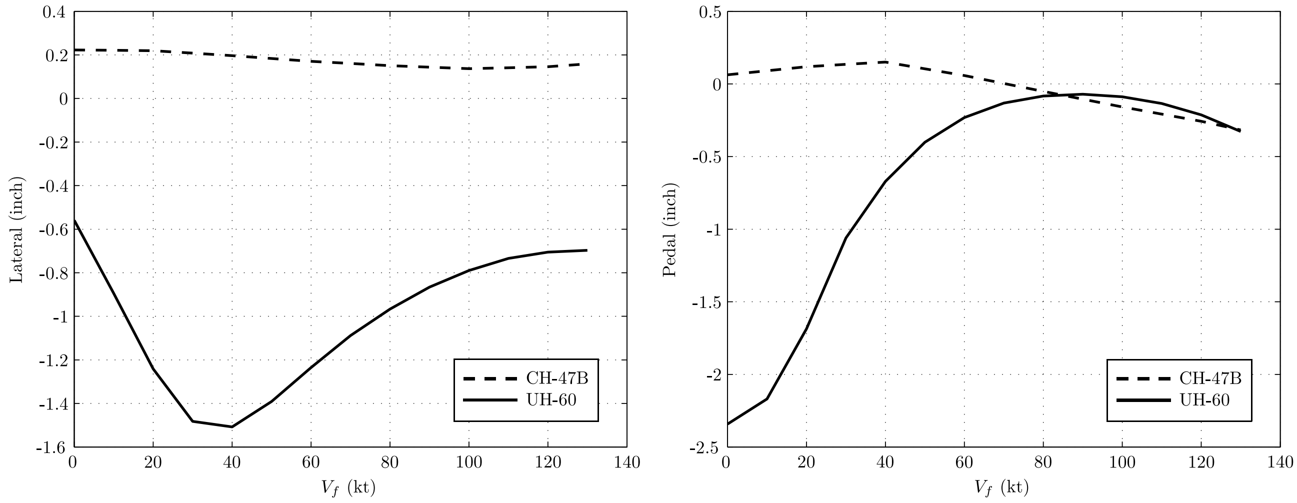
The longitudinal controls of the two vehicles are different. The tandem helicopter uses differential collective to control aircraft pitching whereas the UH-60 uses the standard longitudinal cyclic control. Figure 3(b) compares the displacements of the longitudinal control of the CH-47B and UH-60. The longitudinal control displacement of the UH-60 is almost linear with airspeed. The reason the pilot is required to push the main stick forward, as airspeed increases, is two-fold. Firstly, a forward displacement tilts the rotor thrust vector so that it provides a component of propulsive force to overcome the vehicle's airframe drag. Secondly, there is a natural tendency of the main rotor disc of a conventional helicopter to flap backwards as the dynamic pressure of the rotor blades increase when they approach the advancing side of the disc. The pilot compensates for this by moving the stick forward as airspeed increases. For the tandem helicopter, the differential collective control, δ_b, is linear with airspeed until 40kt. This forward stick motion increases the rotor thrust of the rear rotor, whilst having the opposite effect on the front rotor, to create a component of propulsive thrust. After 40kt, δ_b begins to reduce to balance the pitching moments produced by the front and rear rotors. In forward flight, the front and rear rotor wakes begin to interact requiring suitable control action to trim the aircraft in pitch. Before proceeding, it is interesting to note that earlier tandem helicopters suffered from large pitch attitude angles to trim the vehicle in high speed flight. The solution to this issue, as used in the CH-47B[6], is the application of a longitudinal cyclic control, which is scheduled with aircraft speed, to reduce the excessive pitch attitudes in forward flight.

The lateral controls of the conventional and tandem



(a) Collective Control

(b) Longitudinal Control



(c) Lateral Control

(d) Pedal Control

Fig. 3. Controls of the CH-47B and UH-60 Helicopters in Steady Level Flight

helicopters are presented in Figure 3(c). For the conventional helicopter, a surprising amount of lateral stick displacement, with the negative numbers indicating that stick is moved to the left of the centre stick position, is required to trim the helicopter, Figure 3(c). In the hover, a small lateral control input is necessary to balance the side-force produced by the tail-rotor. As the conventional helicopter transitions into forward flight the stick is displaced further to the left, reaching a minimum value of -1.5inch. As the helicopter leaves the hover, the main rotor wake skews backward due to the effect of the forward airspeed. The rotor wake creates a downwash at the rear of the rotor disc, effectively reducing the angle of attacks of the rotor blades in this portion of the disc. Due to the approximately 90° phase lag between pitch and flap there is a natural tendency of the helicopter to roll to starboard (for a helicopter rotor that rotates anticlockwise when viewed from above). A rather significant left stick input is required in low speed flight to compensate for this effect[7]. This situation occurs on most conventional helicopters. The lateral control input for the tandem helicopter, δ_s, is fairly constant from hover upto 130kt. The pilot is only required to make small lateral control inputs to maintain trim. The tandem helicopter does not feature a tail-rotor and there is a tendency of the lateral forces of the front and rear rotors to balance as they rotate in opposite directions.

The final control to examine is the yaw controls, which are controlled in both vehicles by the application of pedals. The corresponding results are shown in Figure 3(d). For the UH-60 helicopter, the pedal control is displaced by -2.35 inches in the hover to balance the main rotor's torque. The control increases with airspeed and the pedal displacements are almost close to centre by 60kt. At this particular flight condition, the rotor torque is close to its lowest value due to the beneficial contribution of forward flight speed. As the aircraft approaches flight speeds of 120kt, the vehicle's fin provides a significant side-force, thereby offloading the tail-rotor of its anti-torque responsibilities. Consequently, the pedal controls of the conventional helicopter are close to centre in high speed flight. The pedal control inputs of the tandem helicopter are not as significant as the conventional helicopter in low speed flight, Figure 3(d). As the tandem helicopter features two rotors which rotate in opposite directions, the torque from the two rotors generally tend to balance without significant inputs of δ_r. Therefore only small control inputs of the differential lateral cyclic control are required to the balance the modest differences of rotor torques in steady level flight. These small differences in torques, in steady level flight, are due to differential collective control inputs as well as the aerodynamic interactions between the front and rear rotor wakes.

4. STABILITY COMPARISON

The previous discussion explained the trim controls of the tandem and conventional helicopter. Another important flight dynamics feature of the helicopter is its natural modes of motion. Figure 4 presents the predicted Dutch roll, Heave and Pitch modes of the CH-47B and UH-60 helicopters. One distinguishing feature between the two helicopter configurations is the differences in the Dutch roll mode. For the UH-60 helicopter, this lateral oscillatory mode is stable throughout the speed range, with the frequency of the mode increasing with airspeed. In contrast, the Dutch roll mode of the CH-47B is unstable through the speed range, Figure 4. It is interesting to note that the mode's characteristics are insensitive to airspeed for this particular aircraft arrangement. The tandem helicopter does not feature a tail-rotor which reduces the lateral stability of this configuration. As a consequence, the directional stability derivative, N_v, for the tandem helicopter is small, when compared with a conventional helicopter. The fuselage contribution to this derivative is significant and destabilising. In addition, the large inertias of the CH-47B helicopter reduce the damping derivative, N_r[3]. Overall, the directional lateral stability characteristics of the tandem helicopter are not as favourable as the conventional helicopter which has handling qualities implications[3].

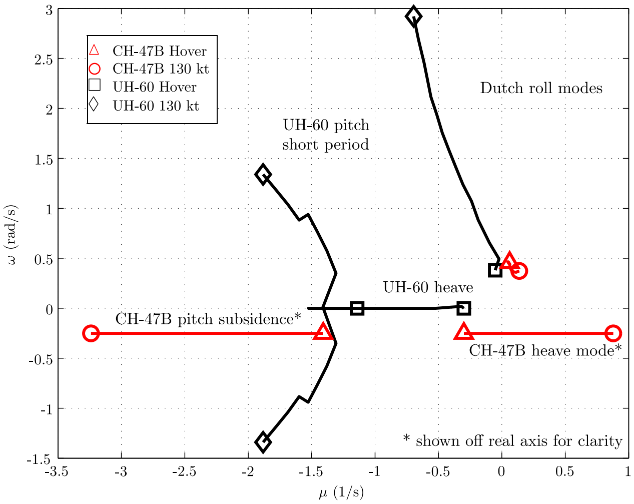


Fig. 4. Dutch roll, Heave and Pitch Modes of the CH-47B and UH-60 Helicopters

Figure 4 also presents the eigenvalues of some of the longitudinal modes of the two helicopters. In the hover, the heave mode of two vehicles is predicted well by the heave damping derivative, Z_w, which is always negative, thereby giving a stable mode. The pitch damping derivative, M_q, also gives a good approximation of the pitch subsidence mode, in the hover. Consequently, the UH-60 and the CH-47B have stable pitch subsidence modes in this flight regime. As the UH-60 moves into forward flight, there is a significant change to the vehicle's longitudinal modes. As seen in Figure 4, the heave and pitch subsidence modes couple together, as forward flight speed increases, and eventually branch off the real axis to form an oscillatory mode. This mode is referred to as the pitch short period mode which loosely resembles the classical short period of a fixed wing aircraft[1]. The mode is characterised by a rapid incidence change with the airspeed remaining fairly constant. This weak longitudinal oscillation is typical of conventional helicopters with articulated main rotors. For example, the Puma SA330 has a similar oscillatory pitch short period mode in forward flight[1]. In contrast, the pitch subsidence and heave modes of the tandem helicopter are given by real roots throughout the speed range. The pitch subsidence mode is stable due to the high pitch damping of the front and rear rotors. When this type of vehicle is subjected to a positive perturbation of q, the thrust of the rear rotor increases whereas the perturbation has the opposite effect on the front rotor. The net effect is that the vehicle is well damped in pitch throughout the flight envelope. In contrast, the heave mode of the tandem helicopter becomes unstable in forward flight. This is primarily due to a large angle of attack instability[3] which is indicated by a positive value of M_w. The interaction of the front and rear rotor wakes has an adverse effect on the angle of attack stability derivative in forward flight[3]. As the tan-

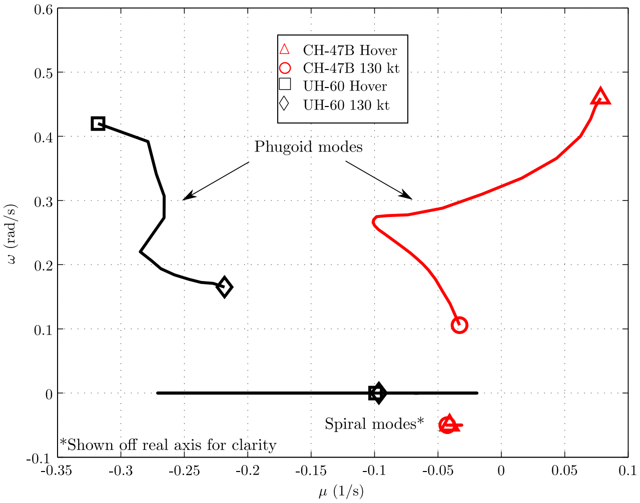


Fig. 5. Phugoid and Spiral Modes of the CH-47B and UH-60 Helicopters

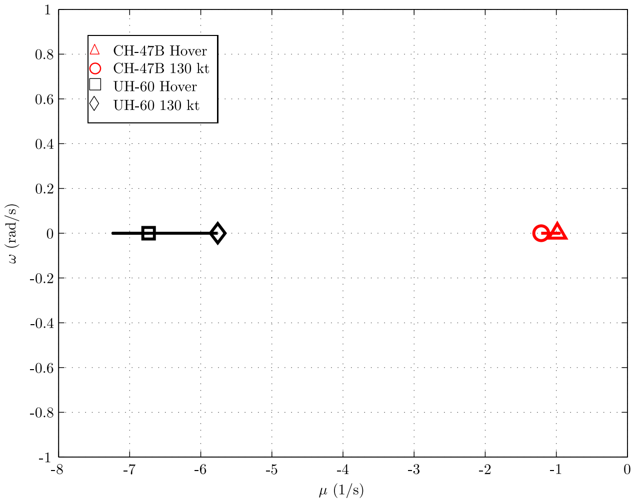


Fig. 6. Roll Subsidence Modes of the CH-47B and UH-60 Helicopters

dem helicopter experiences a positive perturbation of w, the thrust of the front rotor increases as well as the airflow through its rotor disc. This increase of induced velocity through the front rotor disc impinges the rear rotor, thereby reducing its lifting capability. As a result of the aerodynamic interference between the front and rear rotor wakes, a positive perturbation of w increases the thrust of the front rotor but decreases the thrust of the rear rotor. Consequently, there is a destabilising pitch up moment which adversely influences the heave mode in forward flight, Figure 4

Figure 5 compares the phugoid and spiral modes of the CH-47B and UH-60 helicopters. In terms of the spiral modes, both vehicles exhibit small negative roots across the speed range, indicating stability. The stability of the phugoid mode of a conventional helicopter is reliant on the type of main rotor system. Semi-rigid rotor helicopters, like that of the Lynx and the Bo-105, tend to have unstable phugoid modes[1] and it is the rotor type which is the primary reason for the instability[8]. The high stiffness of the rotors create large moments around the rotor hub. When the two helicopters are subject to a perturbation in forward speed, the two rotor systems flap significantly backward, resulting in the fuselage pitching up. As the fuselage pitches up, the main rotor provides a pitch-down moment, with the stability derivative M_q being negative, with this oscillatory motion continuing with the amplitude steadily increasing. However, the phugoid mode of the UH-60 helicopter, with its articulated main rotor, is stable for all airspeeds. The frequency of the weakly damped mode decreases with airspeed. Concerning the phugoid mode of the CH-47B, in low speed flight the mode is predicted to be unstable. However, as airspeed increases, the poles of the phugoid cross over the imaginary of the root locus plot, thereby estimating a stable oscillatory mode in forward flight.

The roll subsidence modes of the two aircraft configurations are presented in Figure 6. As expected, the mode is stable for all airspeeds for both the UH-60 and the CH-47B helicopters. The roll subsidence mode is approximated by the roll damping derivative, L_p. For a rotor this derivative generally tends to be negative, and therefore stabilising, as there is a natural tendency of the rotor to flap to the port side following a positive perturbation of p. For a semi-rigid rotor, the stability of this mode is further increased due to the contribution of the flapping stiffness[1]. For the UH-60 helicopter, with its articulated rotor, the damping of the roll subsidence mode is mainly due to the tilt of the rotor disc following a perturbation of roll rate. The stability of the roll subsidence mode is fairly insensitive to airspeed, Figure 6, with the L_p derivative approximately equal to -6.5/s across the flight envelope. The eigenvalues of tandem helicopter are approximately -1.1/s throughout the speed range, and therefore stable. The front and rear rotors provide stabilising contributions when the aircraft is subject to a perturbation of roll rate. The numerical differences between the eigenvalues of the two vehicles are primarily due to the inertias of both aircraft. For example, the moments of inertia around the x-axis of the UH-60 and the CH-47B are 7632 and 50386 kg.m^2, respectively.

5. AUTOPILOT CONTROL STRUCTURE

The previous section explored the stability results of a tandem and conventional helicopter. It identified certain flight dynamics attributes which need to be addressed

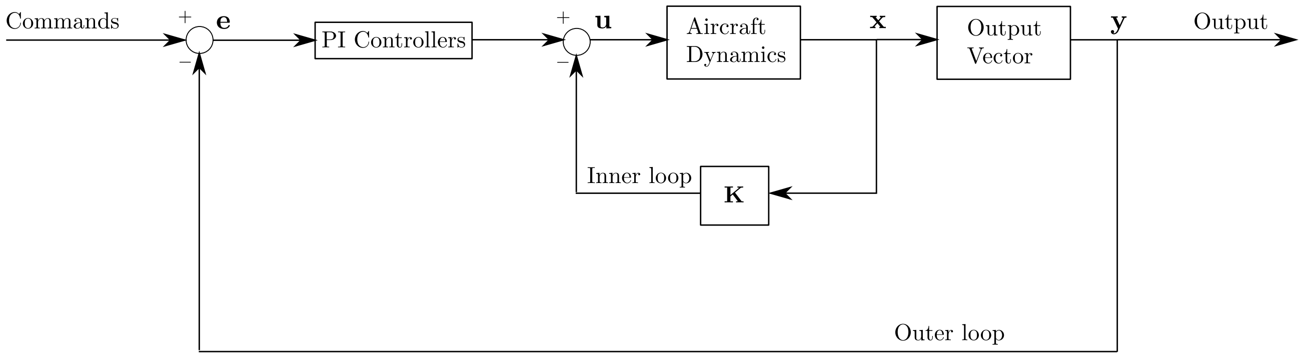


Fig. 7. Control Structure of the Autopilot Function

in the control system design. Recall that the eventual aim of the collaboration between the University of Glasgow and the DST Group is to develop a control generic control structure for OR purposes. Again, it is important to highlight that the goal is not to develop an autopilot for use on the operational aircraft, but to create control functions which will supplement ongoing OR simulations. As a consequence, the design of the autopilot is not subjected to the rigorous testing that would occur if the control system were planned to be implemented on an actual aircraft. The benefit of integrating an autopilot into typical operational scenarios is that realistic control action is generated which is a key indicator of the level of pilot workload and therefore a measure of mission effectiveness. As the operational research by the University of Glasgow and the DST Group plans to focus on various rotorcraft configurations, the controller is designed in a generic manner. The advantage of this approach is that only the controller gains, system and control matrices need to be altered to investigate other helicopter configurations. Given this design approach, Figure 7 shows the basic control structure of the autopilot. The control structure is designed deliberately to be simple, in order to be generic, with one inner and one outer control loop. The commands for this controller, which are represented by the vector $\mathbf{r}$, are the vehicle's airspeed, sideslip velocity, climb speed and track angle

$$\mathbf{r} = \begin{bmatrix} V_{f_{com}} & v_{com} & \dot{z}_{com} & \chi_{com} \end{bmatrix} \quad (1)$$

The required control action, to minimise the error vector $\mathbf{e}$, is determined by Proportional Integral (PI) controllers and the inner loop control law of $\mathbf{u}^* = -\mathbf{K}\mathbf{x}$. The inner loop control law is effectively a Stability Augmentation System (SAS) which stabilises the unstable modes of motion and provides additional damping, were appropriate, to the given helicopter. For example, with the tandem helicopter there is an unstable dutch roll mode across the flight envelope as well as an unstable heave mode, which develops in forward flight. In addition, the the phugoid mode is unstable in low speed flight. For a tandem helicopter simulation, the $\mathbf{K}$ matrix needs to be selected to ensure that these natural modes of motion are stabilised. In terms of the conventional helicopter, the UH-60, there are no unstable modes. However, the vehicle's phugoid and dutch roll modes are lightly damped. Therefore, the gains within the $\mathbf{K}$ matrix may need to be selected to increase the damping of these types of modes so that helicopter can be flown safely within low levels of pilot workload. Taking a broad view of the control system, the inner loop performs the stabilising task whereas the outer loop provides the guidance control. The output vector block in Figure 7 converts the vehicle's states, $\mathbf{x}$, into the output variables required. These variables are

$$\mathbf{y} = \begin{bmatrix} V_f & v & \dot{z} & \chi \end{bmatrix} \quad (2)$$

and the error vector is simply $\mathbf{e} = \mathbf{r} - \mathbf{y}$. Of course, it is the goal of the control system to minimise the error. This can be achieved with the appropriate selection of the gains of the PI controllers and the gain matrix, $\mathbf{K}$.

Case Study

This section presents a case study using the autopilot control system on the CH-47B helicopter. This case study involves the aircraft transitioning from an airspeed of 60ft/s to 80ft/s over a 5s period. The commands for the other controlled states, $v, \dot{z}, \chi$, are set to zero so that the aircraft is only required to change its airspeed. The aim of the controller is to achieve this tracking performance with minimal overshoot. By appropriately selecting the gains for the PI controllers and the gain matrix, $\mathbf{K}$, then good tracking performance can be achieved with Figure 8 showing the results. The controller is able to calculate the control action to force the

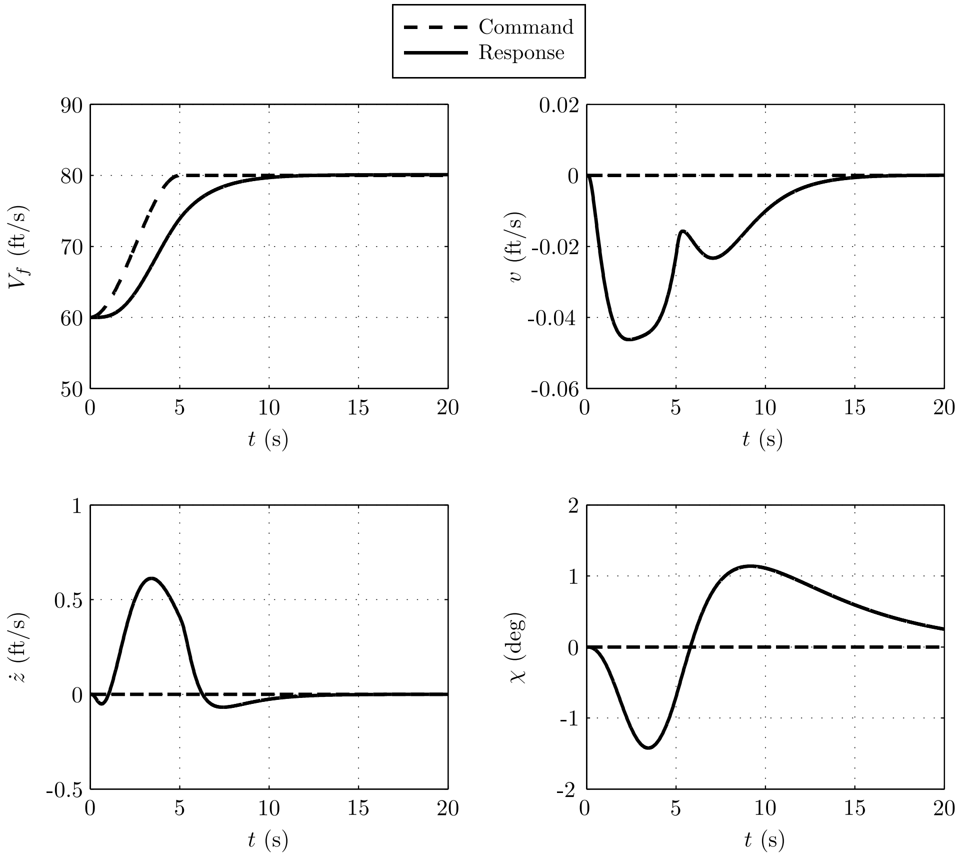


Fig. 8. Case Study Outputs

aircraft to reach an airspeed of 80ft/s at 10s. The airspeed response does lag behind the command signal by a few seconds. It is important to note that the CH-47B is primarily used as a cargo helicopter due to its ability to transport significant payloads. Therefore, it isn't as agile as an attack helicopter such as the AH-64. Consequently, this lag is expected and the performance of the controller can be viewed as acceptable. The selection of the gains results in the airspeed exhibiting a first order response with an insignificant amount of overshoot. With a helicopter, a significant increase of airspeed changes the response characteristics of the vehicle. The inherent cross-couplings of the tandem and conventional helicopter require a high level of pilot skill or an augmented airframe for the aircraft to change speed successfully without major changes to the other aircraft states. Naturally the sideslip, climb speed and track angle all sway from their desired value of 0, but the size of these perturbations is minor and therefore acceptable. As a whole, the tracking performance of the autopilot is satisfactory and achieves its main goal of changing the vehicle's airspeed.

Figure 9 presents the control action calculated by the autopilot control system. This control action is due to a combination of the inner loop control law, $\mathbf{u}^* = -\mathbf{K}\mathbf{x}$, and the controls determined by the four PI controllers. It is interesting to note that satisfactory tracking performance could not be achieved without the inner loop control law. Consequently, it seems evident that all future autopilot control systems, developed by the University of Glasgow and the DST Group collaboration, need to have this inner loop to stabilise the natural motion of the helicopter of interest. The main control action is from the collective lever, δ_c, and the longitudinal stick, δ_b. There is a significant increase in the collective lever position between 0-5s to increase the rotor thrust of the front and rear rotors to accelerate the aircraft forward. The longitudinal stick control, δ_b, is actively used to tilt the rotor vectors forward to provide a component of propulsive force. The result is that between 0-5s the collective and longitudinal controls couple together to accelerate the tandem helicopter forward. Thereafter, suitable control displacements are calculated to arrest the forward acceleration and return the helicopter to a constant airspeed of 80ft/s. The displacements of the lateral stick, δ_s, attempt to reduce the vehicle's sideslip

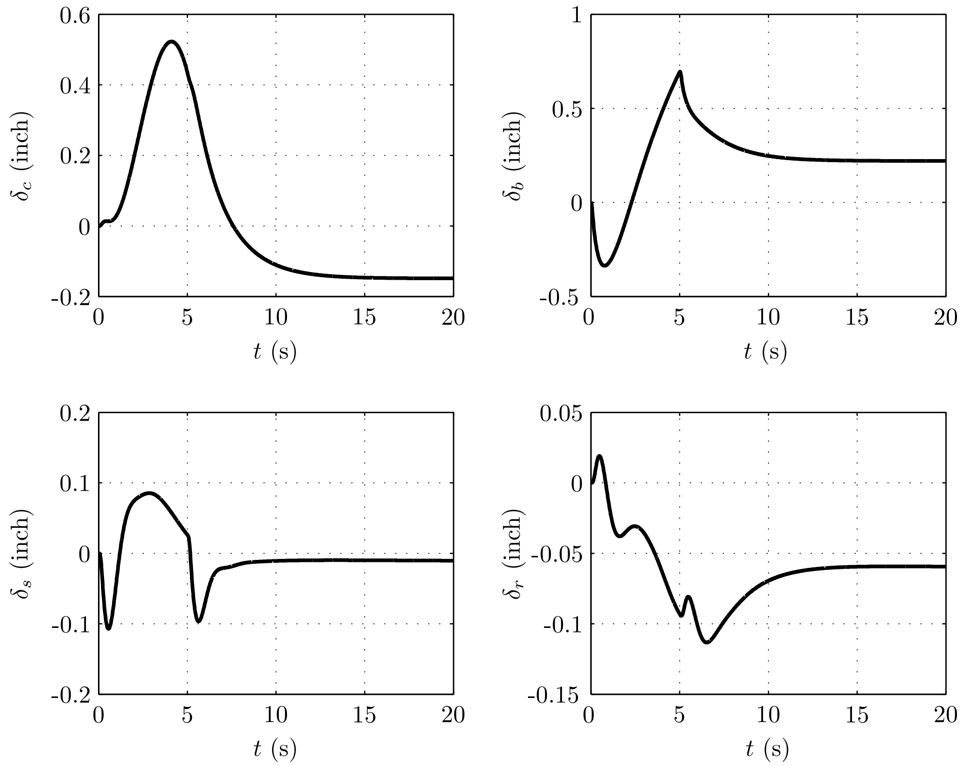


Fig. 9. Control Action Calculated by the Autopilot System

velocity throughout the task. As seen in Figure 8, this control is successful in maintaining the zero sideslip command. The sway in the sideslip velocity is small and therefore acceptable. As expected, small control inputs of the differential lateral cyclic control, δ_r, are required throughout the manoeuvre to balance the different torques of the front and rear rotors, thereby maintaining the aircraft's heading. Similar to the sideslip velocity, there is some sway about the zero tracking command but the values are small. The values for all four control interceptors are fairly constant after the vehicle reaches its target speed of 80ft/s, which is achieved after approximately 10s, highlighting the effective nature of the autopilot control system.

CONCLUSIONS

This paper has reported the ongoing research activities in the University of Glasgow and the DST Group collaboration. Broadly speaking, the aim of the two organisations is to develop a simulation framework capable for use in operational research to analyse helicopter mission effectiveness. The focus of this particular paper was to report the recent activity in developing a generic autopilot control system for the purposes of OR. The eventual goal is to develop a generic autopilot system which can be tailored to be used on a variety of rotorcraft configurations. As highlighted within the paper, the starting point of the controller design is to understand the mechanics of the vehicle. Therefore, the paper investigated the flight mechanics of two helicopter configurations which are of interest to the DST Group. In addition, the paper introduced the control structure of the autopilot system and presented a case study using the CH-47B helicopter model. The following is a list of conclusions from the paper:

1. The tandem helicopter exhibits an unstable dutch roll mode throughout the speed range due to the low levels of yaw damping. The frequency of the mode is insensitive to airspeed. There is also an unstable phugoid oscillation in the hover. As the tandem helicopter moves into forward flight the mode begins to stabilise, however the phugoid mode is lightly damped. An unstable heave mode also develops in high speed flight due to a large angle of attack instability. It is clear that the inner loop of the control system needs to stabilise these unstable modes so that autopilot can effectively guide the tandem helicopter to its designated destination.

2. All the modes of the conventional helicopter in

question are stable throughout the vehicle's flight envelope. There is a significant difference between the dutch roll modes of the tandem and conventional helicopters. The tail-rotor of the conventional helicopter stabilises the dutch roll mode and therefore improves the vehicle's lateral stability characteristics. Although there are no signs of instability for this particular conventional helicopter, the inner loop of the autopilot function will still be required, in all likelihood, to provide stability augmentation to improve the damping of certain vehicle modes. For example, although the phugoid is predicted to be stable, it is lightly damped and the mode may need to be further stabilised so that autopilot can navigate the vehicle along the desired flightpath.

3. The paper also introduced the basic control structure of the autopilot system. It has been designed deliberately so that the control system can be applied to various rotorcraft configurations. The process to change between different vehicles is simple. Only the controller gains, system and control matrices need to be altered to simulate a different rotorcraft configuration. Continuing forward with the work, the aim is to test the control system, using the CH-47 mathematical model, for a variety of operational tasks. After successful testing, the controller will be implemented into the CHOPPA framework so that OR studies can commence.

4. A case study of the autopilot system using the CH-47B helicopter model was presented. The autopilot system successfully determined the control action to force the tandem helicopter to change its flight speed from 60ft/s to 80ft/s. The airspeed response was of a first order nature and there was little overshoot. In addition, the vehicle's sideslip, climb speed and track angle did not change significantly throughout the task, therefore good tracking performance was achieved.

ACKNOWLEDGEMENTS

This work was funded by the DST Group of Australia.

COPYRIGHT STATEMENT

REFERENCES

[1] G.D. Padfield. *Helicopter Flight Dynamics: the Theory and Application of Flying Qualities and Simulation Modelling*. Blackwell Publishing, 2nd edition, 2007. ISBN 13:978-1-4051-1817-0.

[2] M. Ireland, D. Anderson, D.G. Thomson, K.M. Ferguson, A. Chandran, and G. Ibal. CHOPPA-M: Development, Capabilites and Applications to Helicopter Operations Research. In *American Helicopter Society 71st Annual Forum*, Virginia Beach, VA, 2015.

[3] W. Johnson. *Rotorcraft Aeromechanics*. Cambridge University Press, 2013. ISBN 978-1-107-02807-4.

[4] S.J. Newman. *The Foundations of Helicopter Flight*. Edward Arnold, London, 1994.

[5] J.G. Leishman. *Principals of Helicopter Aerodynamics*. Cambridge University Press, 2nd edition, 2006. ISBN 978-0-521-85860-1.

[6] Aaron Ostroff, David Downing, and W. Rood. A Technique using a Nonlinear Helicopter Model for Determining Trims and Derivatives. NASA TN D-8159, 1976.

[7] J. Watkinson. *The Art of the Helicopter*. Elsevier Butterworth-Heinemann, 2004.

[8] A.R.S. Bramwell. *Helicopter Dynamics*. Edward Arnold, first edition, 1976.