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COMPOUND HELICOPTER LOAD ALLEVIATION IN FORWARD FLIGHT

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Abstract

The potential benefits of using redundant controls on a compound helicopter for manoeuvre load alleviation whilst optimizing handling qualities are investigated. The research is focused on forward flight lateral (roll) manoeuvres and hub loads. The main control effectors of interest are the ailerons and lateral cyclic pitch. A nonlinear simulation model of a compound version of the UH-60A Black Hawk helicopter is developed. Open-loop responses of the simulation model indicate that both the ailerons and lateral cyclic pitch can be used effectively for lateral control. However, these controls have a profoundly different effect on the hub loads. An analysis of the control strategy in trim, including other redundant controls such as compound thrust, reveals that the trim strategy has a major impact on steady state loads and the required power. Hence, there is an opportunity to optimize the control allocation strategy for load alleviation purposes. System identification techniques are used to obtain accurate linear models of the lateral dynamics for control law design. Roll attitude command, attitude hold (ACAH) control laws are developed for different gearing ratios between lateral cyclic pitch and aileron deflection. The control laws are optimized for handling qualities. The minimization of hub loads is the secondary objective. It is demonstrated that compared to conventional helicopter mode control or fixed-wing mode control, predicted handling qualities can be improved and hub loads can be reduced significantly (in the order of 30%-50%) for moderate to large amplitude manoeuvres if the gearing ratio between lateral cyclic pitch and aileron deflection is carefully selected.

1. INTRODUCTION

The compound helicopter gains interest as operational needs push future rotorcraft capabilities beyond current standards. The compound helicopter is investigated as part of the Future Vertical Lift Program to replace the entire U.S. Army helicopter fleet [1]. The compound helicopter resembles a mix between a fixed-wing aircraft and a conventional helicopter. It features a controllable rotor as well as wings, elevator, ailerons and propeller(s) for thrust. Increased agility is achieved by the unique combination of controls and the maximum flying speed is expanded by unloading the rotor lift and redistributing it over the wings. In the UH-60 airloads program it was demonstrated that conventional helicopters can experience critical loads when high speed manoeuvres are conducted [2]-[5].

Compound helicopters operate at even higher speeds and therefore manoeuvre loads are expected to increase compared to conventional helicopters. At the same time, there is an opportunity to use the redundant set of controls to alleviate manoeuvre loads.

Research efforts into the use of load alleviation using redundant controls specifically for compound helicopters are scarce. Saetti and Horn [6], [7] evaluated the use of load alleviation control laws which use rotor state feedback and redundant controls to minimize vibratory loads (pitch link loads) on a compound version of the UH-60A Black Hawk. It was demonstrated that load alleviation can be achieved without a degradation in predicted handling qualities [7]. The compound helicopter simulated in the above-mentioned studies is similar to the experimental aircraft designated Speed Hawk [8]. Other research by Thorsen and Horn [9], [10] was focused on achieving the best performance and handling qualities for this compound helicopter without including load alleviation functionalities in the control systems.

The aim of the current research is to investigate the potential benefits of using redundant controls for lateral manoeuvres in forward flight to maximize handling qualities whilst minimizing hub loads. For this purpose, various roll attitude command, attitude hold (ACAH) control laws are developed which use different ratios of lateral cyclic pitch and aileron deflection. These two redundant controls have a different effect on the hub loads and on the compound helicopter dynamics. Classical techniques are used to design the ACAH control laws. A compound version of the UH-60 Black Hawk serves as test case in the current research. An impression is given in Figure 1. This compound helicopter is similar to the one studied in references [6], [7], [9], [10]. The main rotor of this compound helicopter is driven by the engine in all flight phases.

Figure 1: Impression of the compound version of the Black Hawk helicopter (Image adapted from: [11])

This article is structured as follows. A nonlinear simulation model of a compound helicopter is developed and presented in Section 2. This nonlinear simulation model is first used to gain a physical insight in the effect of different control strategies on handling qualities and hub loads for lateral manoeuvres in forward flight. Linear models are subsequently derived by means of system identification techniques. The approach to design the control laws is described in Section 3. The analysis of the control laws implemented on the nonlinear simulation model is presented in Section 4. The analysis focuses on the trade-off between predicted lateral handling qualities and hub loads. Finally, conclusions and recommendations are made.

2. SIMULATION MODEL

2.1. Nonlinear model description

A multi (rigid) body dynamics model of a compound helicopter was constructed to simulate high speed manoeuvring flight. The core of this model is the swashplate mechanism and the rotor blades. This model was based on the work of Pastorelli et al. [12]. A schematic overview of the multi body dynamics model is presented in Figure 2. The main rotor is represented as a blade element model with a Peters-He inflow model [13]. Aerodynamic coefficients are found from quasi-steady look-up tables [14]. Blades are assumed to be rigid and feature a feather and flap hinge. The fuselage aerodynamics are interpolated from test data. The empennage is modelled using 2D look-up tables to compute the aerodynamic coefficients. The wing and push propeller, unique to the compound helicopter type, are modelled by a non-linear lifting line [15] and a point force acting near the tail respectively. The tail rotor model used is described in detail in references [16] and [17]. A summary of the aero-propulsive models described above is presented in Figure 3. The actuators are modelled as second order systems with rate and position limits. The parameters defining the actuator models provided in Table 1 were based on the work of Howlett [14].

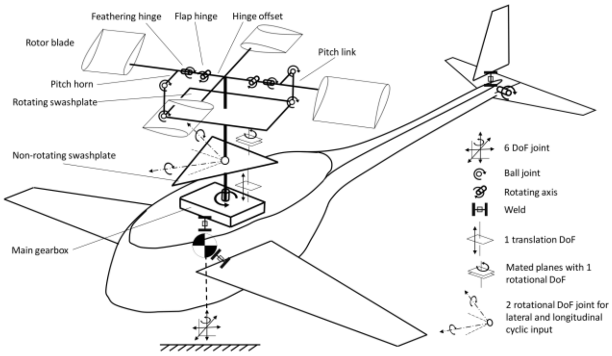

Figure 2: Overview of the multi (rigid) body dynamics model.

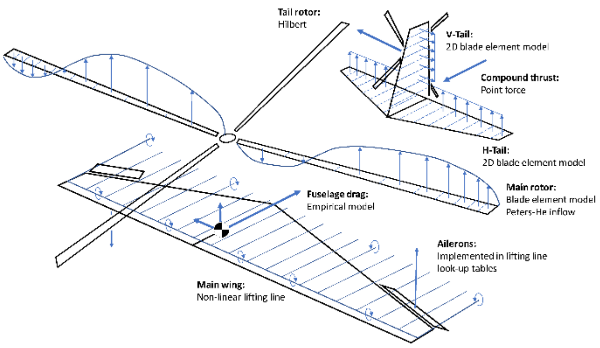

Figure 3: Overview of the aero-propulsive models

	Lateral cyclic pitch θ_{1c}	Aileron deflection δ_a
Rate limit [deg/s]	±45	±45
Position limit [deg]	± 8	±20
Natural frequency ω_n [rad/s]	29.6	29.6
Damping ratio ζ [-]	0.7	0.7

Table 1: Nonlinear second order actuator models.

The ‘fly-to-trim method’ [18] was implemented to determine the trim settings for an arbitrary flight condition. This method uses a basic flight controller representing a virtual pilot to find the controls associated to an equilibrium situation. In the current

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research, the ‘fly-to-trim method’ only makes use of the helicopter controls. Other redundant controls such as the ailerons or horizontal stabilizer can be set at a fixed constant value in the trim process. After completion of the trim process, time domain simulations can be conducted with user specified input signals for all controls.

Throughout the complete paper, a single flight condition is considered. The compound helicopter starts each manoeuvre in steady, straight, level and non-sideslipping flight at sea level conditions and 120 kts forward flight. Only for model verification purposes (Section 2.2) other airspeeds are considered.

2.2. Model verification

The nonlinear simulation model without wings, representing a conventional UH-60A Black Hawk, was compared to a commercial rotorcraft flight dynamics simulation model (FLIGHTLAB, [19]) for verification purposes. The FLIGHTLAB model used has, to a large extent, the same fidelity. Nevertheless, there are some small differences. For example, the nonlinear simulation used in the present research has a more detailed model of the swashplate mechanism. A comparison of the helicopter attitude and rotor flap angles in trim as a function of airspeed is presented in Figure 4 and Figure 5.

In these figures, φ and θ represent the pitch and roll attitude of the compound helicopter. The main rotor individual blade flap angles (β_i) are converted to multi blade coordinates using the following equations [20].

(1) $$\beta_0 = \frac{1}{N_b}\sum_{i=1}^{N_b} \beta_i$$

(2) $$\beta_{1c} = \frac{2}{N_b}\sum_{i=1}^{N_b} \beta_i \cos\psi$$

(3) $$\beta_{1s} = \frac{2}{N_b}\sum_{i=1}^{N_b} \beta_i \sin\psi$$

In these equations, the angle ψ represents the blade azimuth angle and N_b represents the number of rotor blades. It can be observed from Figure 4 that the pitch (θ) and roll (φ) trim angles have the same trend as a function of airspeed. There is a small offset compared to the FLIGHTLAB model. The same conclusion can be drawn for the coning angle (β_0), longitudinal disc tilt (β_{1c}) and lateral disc tilt (β_{1s}). The comparison demonstrates that both models are in close agreement. Following this verification step, the nonlinear lifting-line model of the main wing was compared to a vortex-lattice model. Finally, the dynamic response of the model was compared to FLIGHTLAB. For sake of brevity, results for these last two verification steps are omitted from this paper. More details are provided by Declerck [21].

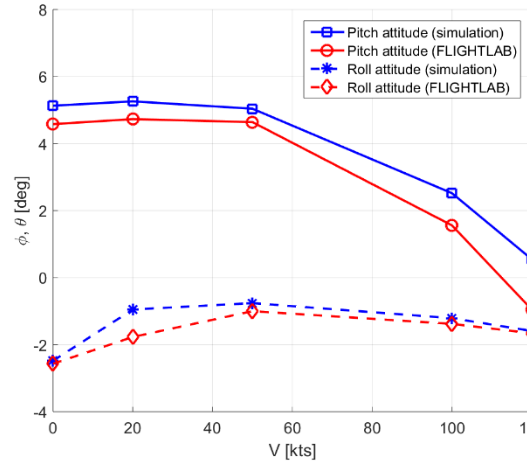

Figure 4: Verification of helicopter (no wings) pitch and roll attitude in trim as function of airspeed

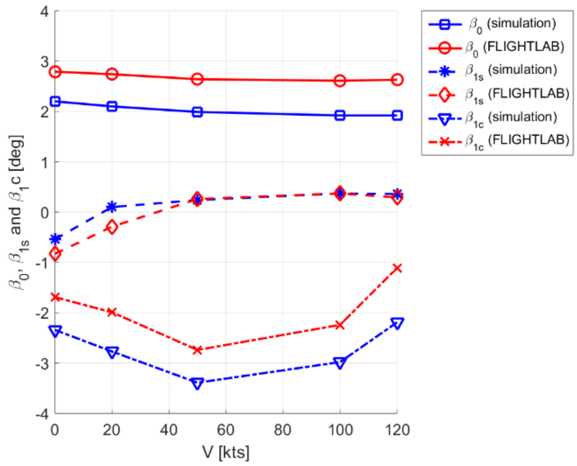

Figure 5: Verification of rotor trim flap angles as function of airspeed

2.3. Trim analysis and open-loop model responses

The nonlinear simulation model was first used to analyse the effect of different control strategies on hub loads and handling qualities in forward flight. Both the trim condition and open-loop model responses were investigated. For the trim analysis, the horizontal stabilizer deflection δ_{hor} (II-III), compound thrust $T_{compound}$ (IV-V), rotor rpm Ω (VI-VII) and aileron deflection δ_a (VIII) are varied. This enables the helicopter to offload both the lifting and propulsive function of the main rotor and influence the hub loads and flight performance (power required).

Table 2 shows the results of the trim analysis, the roman numbers indicate the variation of the trim conditions according the different control inputs as presented above. The trim control strategy can have a profound effect on the hub loads (lateral and longitudinal forces and moments) both in terms of the mean value and the amplitude of the oscillatory load. Furthermore, the total required power ($P_{tot,req}$) is strongly related to the trim strategy. A horizontal stabilizer deflection (δ_{hor}) directly influences the pitch equilibrium. A positive horizontal stabilizer deflection lowers the required longitudinal cyclic pitch (θ_{1s}) which consequently results in less longitudinal flapping and a lower longitudinal hub bending moment M_Y. The main rotor can be unloaded by increasing the nose-up attitude of the fuselage allowing the wing to generate more lift, hence reducing the rotor power.

Compound thrust ($T_{compound}$) can be used to counter the fuselage drag. Both the propulsive and lifting function of the main rotor are thereby alleviated. The longitudinal rotor loading F_X and M_Y are reduced as the compound thrust alleviates the longitudinal cyclic. Lowering the rotor speed (RPM) primarily has an effect on the required power. This effect is also reported in [22]. A constant aileron deflection (δ_a) will lower the power required by pushing the lift more outboard over the advancing blade. The required cyclic input to counter this aileron deflection primarily affects the lateral equilibrium and thereby the lateral loads M_X and F_Y.

		Control strategy							
	Variable	Baseline	II	III	IV	V	VI	VII	VIII
Controls	δ_{hor} [deg]	0	5	-5	0	0	0	0	0
	$T_{compound}$ [N]	0	0	0	2500	5000	0	0	0
	Ω [rad/s]	27	27	27	27	27	24.3	21.6	27
	δ_a [deg]	0	0	0	0	0	0	0	3
	θ_0 [deg]	15.3	15.4	15.4	14.1	12.1	16.4	18.0	15.2
	θ_{1c} [deg]	-1.06	-0.94	-1.08	-1.02	-0.48	-1.21	-1.48	-3.52
	θ_{1s} [deg]	-5.08	-2.04	-8.78	-3.56	0.97	-6.16	-7.71	-4.95
Rotorcraft attitude	θ [deg]	-1.87	-4.25	0.47	-0.84	0.59	-1.69	-1.58	-1.80
	φ [deg]	-1.61	-1.70	-1.41	-0.95	-1.22	-1.29	-1.79	0.41
Blade flap angles	β_0 [deg]	1.26	1.55	1.01	1.02	0.57	1.63	2.11	1.24
	β_{1c} [deg]	-2.04	1.34	-6.11	-1.01	0.82	-2.08	-2.01	-2.29
	β_{1s} [deg]	0.21	0.15	0.34	0.17	0.29	0.28	0.39	2.38
Main rotor hub loads	F_X (mean) [N]	3115	540	5006	1707	132	3344	3325	3152
	F_X (amplitude) [N]	467	227	427	353	281	608	762	524
	F_Y (mean) [N]	629	810	576	474	205	658	797	2759
	F_Y (amplitude) [N]	271	116	596	148	218	385	498	385
	F_Z (mean) [N]	45900	54902	37191	40507	31576	45695	44051	45658
	F_Z (amplitude) [N]	2635	1996	2074	2687	2664	3106	2596	2568
	M_X (mean) [Nm]	4255	4299	4223	3772	2499	4090	4048	17986
	M_X (amplitude) [Nm]	969	611	2627	970	961	972	468	1239
	M_Y (mean) [Nm]	10615	7564	29926	5173	4810	8553	6377	11226
	M_Y (amplitude) [Nm]	1027	805	2561	1098	1178	695	436	1183
	M_Z (mean) [Nm]	26916	27980	26649	21777	15632	25591	25430	25796
	M_Z (amplitude) [Nm]	1289	1643	3597	694	1159	973	512	3499
Performance	$P_{tot,req}$ [kW]	727	755	720	742	730	623	549	697
	Rotor-lift share* [%]	68	81	55	60	47	65	68	67
	Wing-lift share* [%]	34	18	49	40	50	36	35	35

* Note: Other components such as the horizontal tail and fuselage also contribute to the total lift force

Table 2: Effect of redundant controls on trim condition at 120 kts forward flight.

The baseline trim condition is defined by a zero degrees deflection of the horizontal stabilizer and ailerons, 100% RPM of the main rotor (27 rad/s) and zero compound thrust. This baseline trim condition is used as starting point for all manoeuvres presented and analysed in the remainder of this article. It is not an optimal condition but serves merely as reference.

The open-loop responses of the nonlinear simulation to a lateral cyclic pitch input and an aileron input are investigated. Pulse inputs with a magnitude of 50% of the maximum control input are simulated. All manoeuvres are turns to the right. Results are displayed in Figure 6 and Figure 7. The duration of the pulses are chosen such that both manoeuvres have approximately the same magnitude in terms of the final roll attitude.

It can be observed that the lateral hub moment (M_x) and force (F_Y) due to lateral cyclic pitch and aileron pulses have an opposite sign. This behaviour is strongly related to the lateral flapping response. The lateral cyclic pitch control input directly causes a lateral flapping of the rotor disc. When the compound helicopter rolls due to an aileron control input, the lateral flapping is primarily a result of the fuselage rolling motion. Consequently, the lateral hub moment and force due to an aileron input are delayed and the amplitude of the oscillations is smaller.

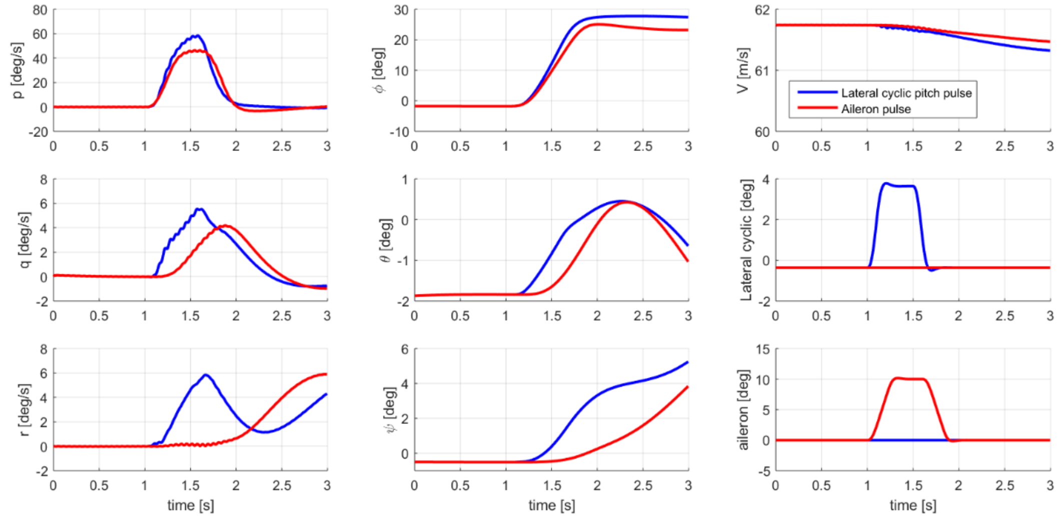

Figure 6: Open-loop time domain responses to a lateral cyclic pitch or aileron pulse - helicopter motion and control angles

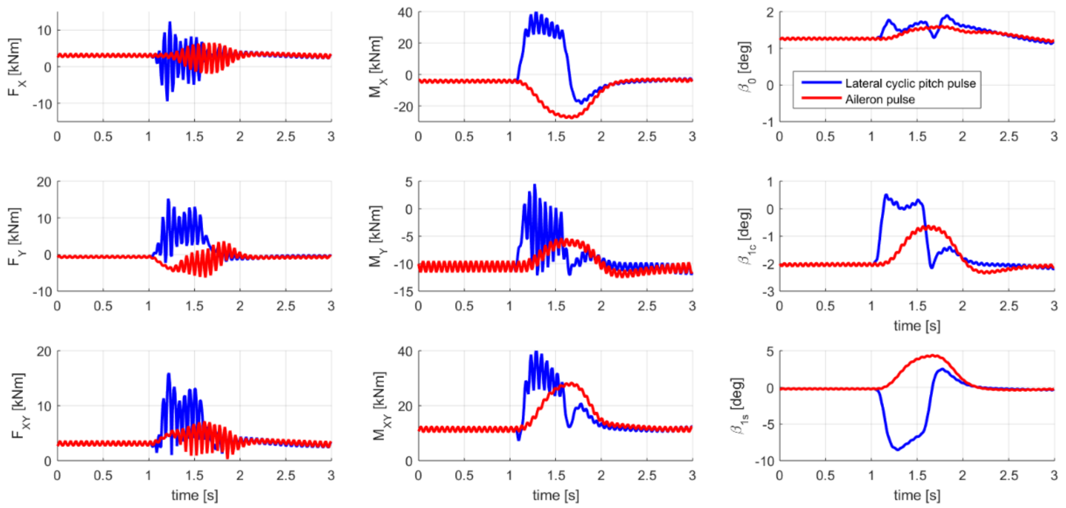

Figure 7: Open-loop time domain responses to a lateral cyclic pitch or aileron pulse – hub loads (lateral and longitudinal forces and moments) and rotor flap angles

The total hub moment and force, defined in the equations below, are also displayed in Figure 7.

(4) $M_{XY} = \sqrt{M_X^2 + M_Y^2}$

(5) $F_{XY} = \sqrt{F_X^2 + F_Y^2}$

The primary response of the compound helicopter in terms of the rolling motion is comparable for both inputs. The roll response due to the aileron appears less fast but this is partly caused by the actuator rate limit. As expected, the off-axis responses in pitch and yaw are smaller when the aileron is used. One should note that due to the asymmetric nature of the rotor aerodynamics in forward flight, results will be different when left and right turns are compared. For sake of brevity, only right turns are presented in this paper. The different nature of the lateral hub loads responses provides an opportunity to distribute roll commands over the lateral cyclic pitch and the aileron in order to minimize these loads.

Summarizing, the preliminary analysis of the open-loop responses with the nonlinear simulation model indicates amongst others that the combined use of lateral cyclic pitch and aileron can potentially be used to optimize handling qualities and at the same time minimize hub loads. Also investigated was the effect of control strategy the trim condition and dynamic loads.

2.4. System identification

The system identification techniques described in [23] and [24] were employed to obtain linear models of the compound helicopter at 120 knots forward flight for control law design purposes. The nonlinear model was first trimmed in the specified flight condition and subsequently subjected to a frequency sweep on either the lateral cyclic pitch command channel or the aileron deflection command channel. The amplitude, duration, maximum and minimum frequency of the sweep were selected based on the methods described in [23] and [24]. The measured output signal of the compound helicopter simulation model is the roll rate (p) defined in the body axes system. The Matlab routine *tfestimate* was used to determine linear models in the form of transfer functions. This routine makes use of Welch's averaged periodogram method. The transfer functions provide the relation between the input signal in terms of the aileron deflection (deg) or lateral cyclic pitch (deg) and output signal which is the roll rate (deg/s). The transfer functions are presented in equations 6 and 7. The lowest order transfer functions that provide good accuracy were finally selected.

(6) $T_{cyclic,p}(s) = \frac{16.475s+1918.1}{s^2+22.388s+124.14}$

(7) $T_{aileron,p}(s) = \frac{44.760s^2+54.864s+139.30}{s^3+10.278s^2+16.724s+31.375}$

A comparison of the nonlinear simulation model and the linear models is presented in Figure 8 - Figure 10. The input signal presented in Figure 8 is a one degree command relative to the trim control setting for a duration of one second. The actuator dynamics and rate limits can be observed in this figure.

It can be seen that both linear models are in close agreement with the nonlinear simulation model for the specified time domain input. The periodic oscillation is not captured by the linear model as expected.

One should note that the linear models are in fact linear-time-invariant (LTI) systems which do not capture information about the dynamic hub loads. If accurate models or test data are available, it is possible to derive linear time periodic systems which are suitable to predict the effect on loads [25].

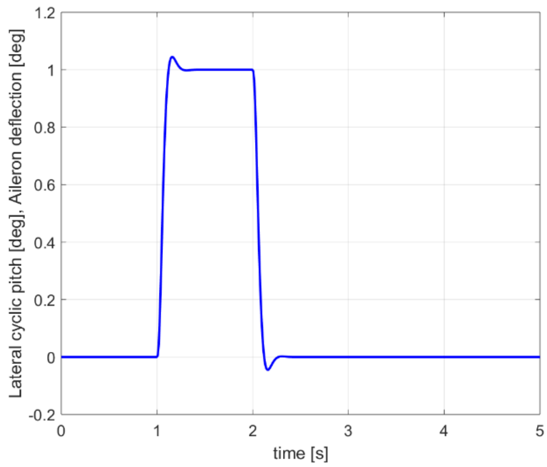

Figure 8: Time domain input signal (relative to trim) for comparison of linear and nonlinear models.

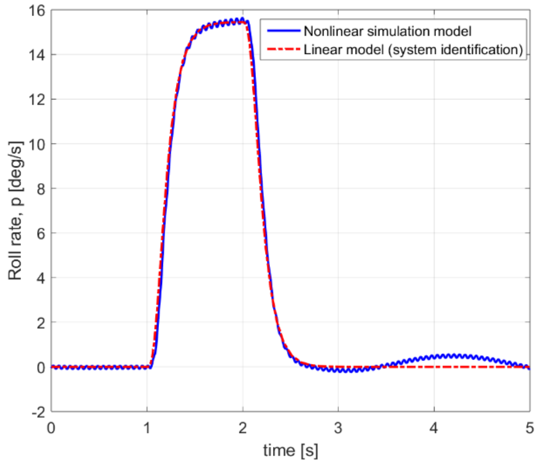

Figure 9: Comparison linear and nonlinear simulation model for a lateral cyclic pitch input

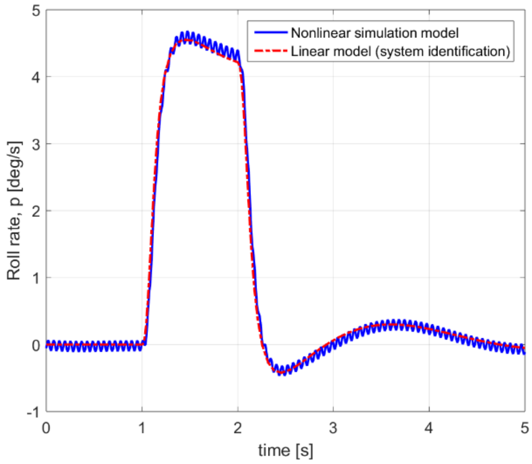

Figure 10: Comparison linear and nonlinear simulation model for an aileron input

3. CONTROL SYSTEM DESIGN

3.1. Control system architecture

Based on the linear models presented in Section 2.4, several lateral attitude command attitude hold control laws (ACAH) were developed with a high level structure as presented in Figure 11.

The roll ACAH control system is essentially a proportional feedback control law. The command created by the proportional gain is distributed over the lateral cyclic pitch angle and the aileron deflection angle by means of control allocation gains which determine the relative deflections of the two controls. All possible values for the control allocation gains are presented in the following equations

(8) $K_{aileron,1} \in \{-1, -0.9, -0.8, \ldots, 0.8, 0.9, 1\}$

(9) $K_{cyclic,1} \in \{0, 0.1, 0.2, \ldots, 0.8, 0.9, 1\}$

Hence, in the most extreme scenarios, only a single control is used (for example:. $K_{aileron,1} = 0$, $K_{cyclic,1} = 1$) or the deflection of one control is in the opposite sense of the other control (for example:. $K_{aileron,1} = -0.7$, $K_{cyclic,1} = 0.2$). The lateral cyclic pitch and aileron inputs are scaled such that a command of unit magnitude by the proportional control system results in a maximum input (up to the actuator limits). The pilot stick input is translated into a roll attitude command by means of a fixed gearing ($K_{gearing}$).

3.2. Selection of optimal gains

The control system architecture presented in the previous paragraph was combined with the linear compound helicopter models presented in section 2.4. An optimal proportional gain (K_p) was determined for each possible combination of control allocation gains. The process to obtain an optimal proportional gain is presented in Figure 12.

The control system tuning process consists of seven steps. First a combination of control allocation gains is selected. Next, it is analysed for which range of proportional gains, the relative stability margins are met. The robust stability requirements from MIL-F-9490D [26] are used to determine whether the relative stability of the control law is satisfactory (Gain Margin < 6dB and Phase Margin < 45 degrees). The range of feasible proportional gains is divided in a discrete set of gains. For each proportional gain, a set of handling qualities criteria and time domain criteria are computed. The list of criteria can be observed in Figure 12. All proportional gains which result in a system which is prone to pilot induced oscillations (PIO) according to ADS-33 [27], are eliminated. Next, all proportional gains which do not provide good tracking of the roll angle are excluded. This is defined by the steady state error and the percentage overshoot following a step command. The remaining set of gains is classified based on the predicted handling qualities level (level 1, 2 or 3). Only the proportional gains which deliver the best handling qualities level are taken to the next step. In the final step, all remaining proportional gains deliver good tracking, provide the best possible handling qualities and comply with relative stability requirements. From this final set, the best gain is chosen based on the weighted performance index provided in equation 8. What is ‘best’ in this final step is subjective and can be specified by the control system designer.

The process described above resulted in a set of roll ACAH control systems with different control allocation gains. All these control systems are subsequently implemented on the nonlinear model in order to analyse their performance in terms of handling qualities and loads. The results of this analysis are presented in the following section.

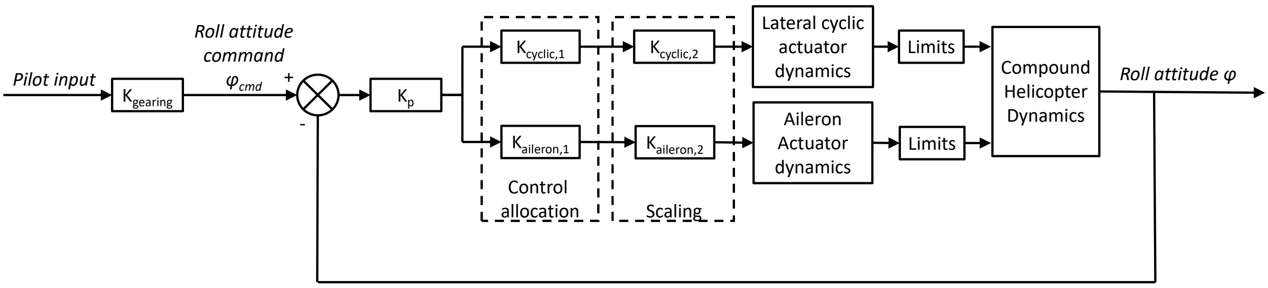

Figure 11: Control system architecture

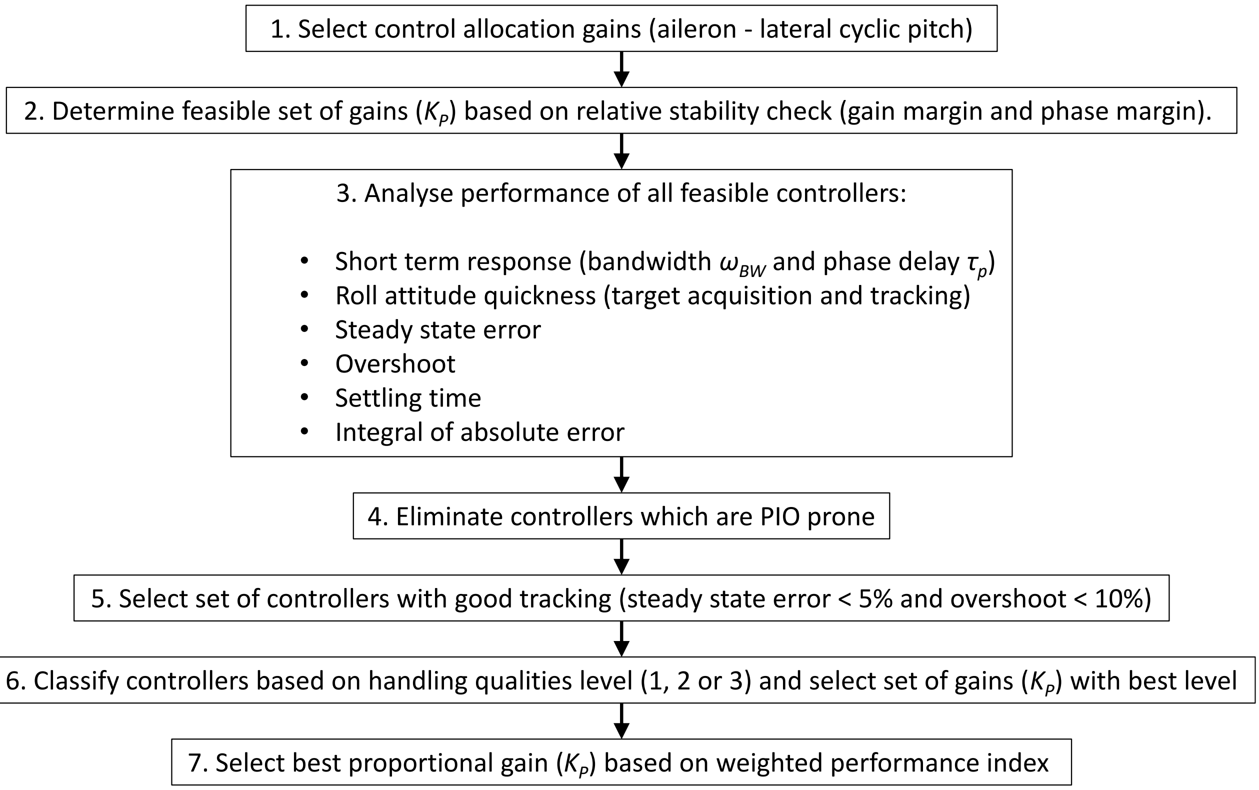

Figure 12: Control system tuning process

4. RESULTS

Three roll ACAH control laws are presented in this section. The first control law only makes use of lateral cyclic pitch and the second control law only makes use of the aileron. Hence, these control laws are representative for helicopter mode and airplane mode control. The third control law is based on the control allocation gains that provide the best hub load alleviation ($K_{aileron,1} = 1, K_{cyclic,1} = 0.6$)

4.1. Closed-loop time domain responses

Time domain responses of all relevant parameters for a step roll command with the third control law (mixed controls) are presented in Figure 13 and Figure 14. Accurate tracking of the roll angle can be observed. The steady state error is 1% and the overshoot is 5%. A small off-axis response in the pitch axis is present. The compound helicopter initially pitches up by approximately 2 degrees relative to the trim condition. Pitch due to roll coupling is deemed not to be objectionable to the pilot as required by ADS-33 [27]. The total hub moment shows only relatively small variations because the longitudinal hub moment decreases in magnitude when the lateral hub moment increases in magnitude. The shape of the response of the hub loads is correlated to the control input, the rotor flap angles and the helicopter motion.

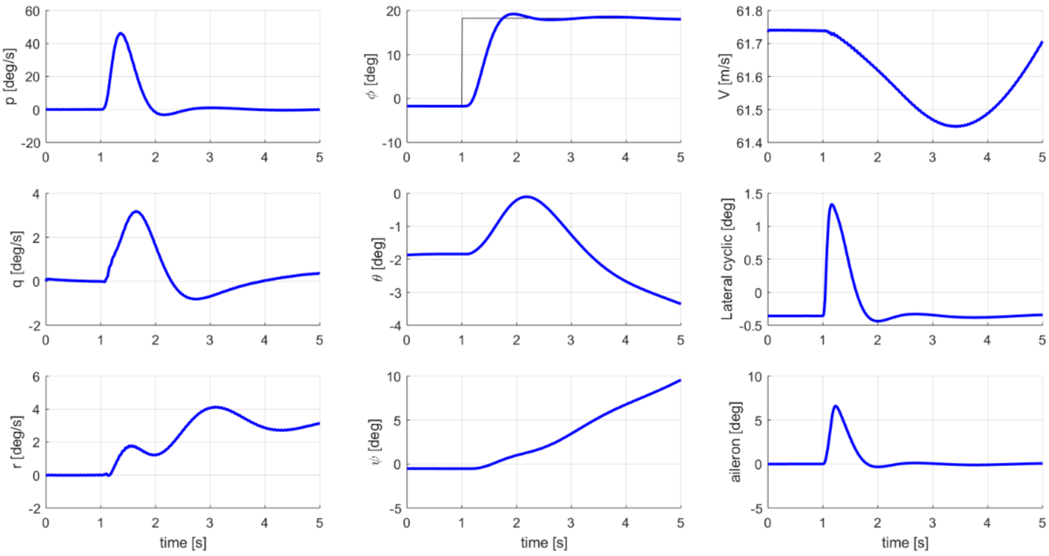

Figure 13: Helicopter motion and control inputs for a roll attitude command of 20 degrees with optimal distribution between lateral cyclic pitch and aileron for hub load alleviation

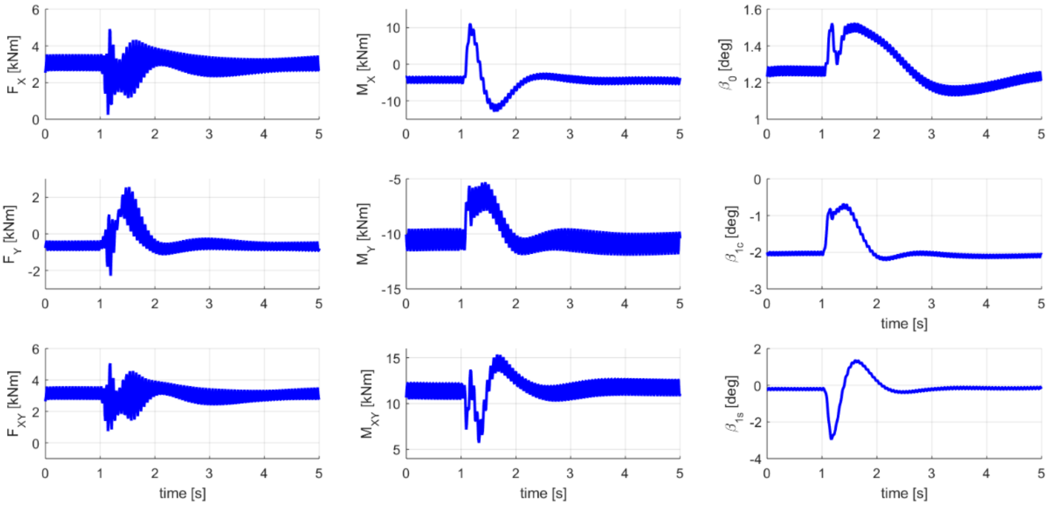

Figure 14: Hub loads and rotor flap angles for a roll attitude command of 20 degrees with optimal distribution between lateral cyclic pitch and aileron deflection for hub load alleviation

Next, the total hub forces and total hub moments are compared for the three control laws (see Figure 15). One can see that when lateral cyclic pitch is used as only control effector, the total hub moment shows a large increase of about a factor two directly after the roll attitude command. This behaviour is primarily caused by an increase in the lateral hub moment and can be observed in Figure 7 as well. An increase of the total hub moment of comparable magnitude can also be seen when the ailerons are the only effectors. In that situation, the peak hub moment is delayed as explained in Section 2. It is of key importance to realize that the lateral hub moment and force both have an opposite sign compared to the case where lateral cyclic pitch is used. Since the total magnitude in hub loads is evaluated, the difference in sign does not make a difference when comparing aileron control with lateral cyclic pitch control. However, when both controls are used in an optimal fashion, the lateral hub moment and force resulting from the lateral cyclic pitch input are largely negated by the lateral hub moment resulting from the aileron input. Hence, the magnitudes of the total hub moment and force are both reduced significantly. A detailed quantification of the load reduction is presented in Section 4.3.

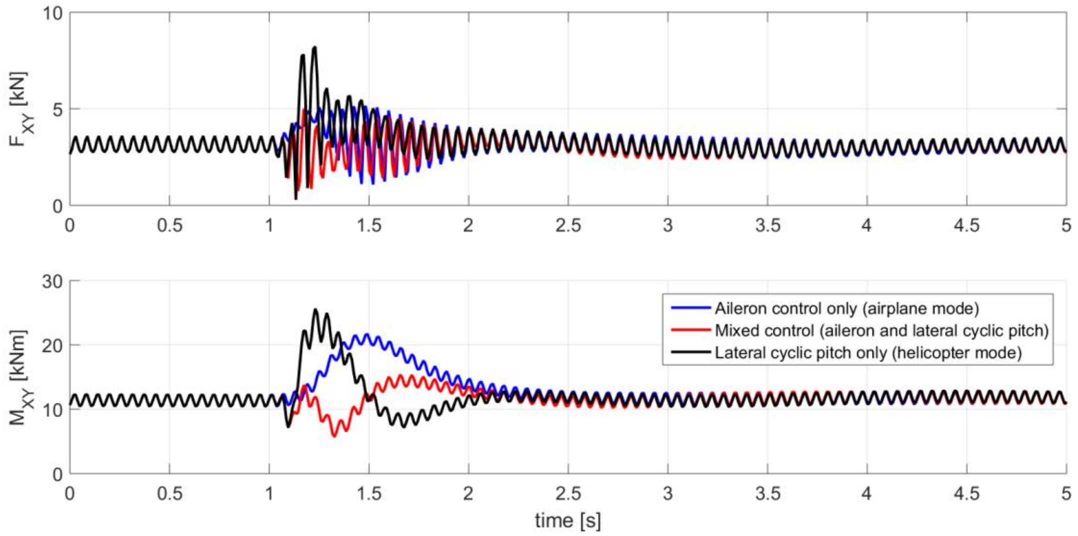

Figure 15: Hub loads comparison for three control laws (roll attitude command of 20 degrees)

4.2. Handling qualities

Next, the handling qualities of the three control laws are analysed. The bandwidth and phase delay are presented in Figure 16. The roll attitude quickness for target acquisition and tracking mission task elements in forward flight is provided in Figure 17. Other handling qualities criteria such as the inter-axis coupling and the yaw response are not investigated. The open-loop time domain analysis in Section 2 already demonstrated that the predicted handling qualities in terms of inter-axis coupling are good. The yaw response and roll-sideslip coupling will be directly influenced by a directional control law and turn coordination system. These elements are not part of the control law design in the current research.

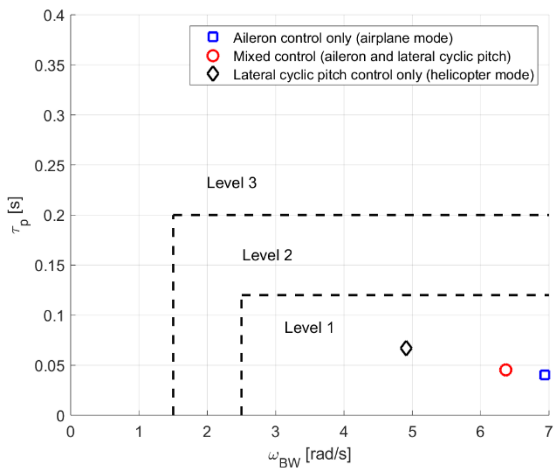

Figure 16: Requirements for small-amplitude roll attitude changes in forward flight. Target acquisition and tracking mission task elements.

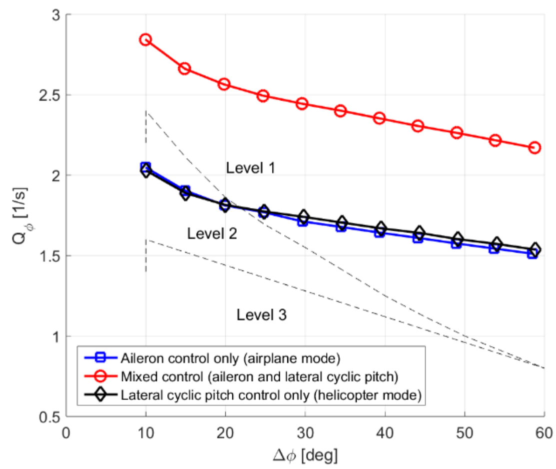

Figure 17: Comparison of roll attitude quickness (target acquisition and tracking mission task elements) for different control strategies.

The predicted handling qualities for small-amplitude roll attitude changes are level 1 for all control laws. If the aileron is used, a higher bandwidth can be achieved. The predicted handling qualities in terms of attitude quickness is almost identical for the helicopter mode and airplane mode control laws. For roll attitude changes up to 20 degrees, the predicted handling qualities are level 2 whereas for larger attitude changes the predicted handling qualities are level 1. When the mixed controls are used, the roll attitude quickness is increased significantly and predicted handling qualities are level 1 for all roll attitude changes. This can be explained by the fact that a control law that uses both control has inherently more control power at its disposal and thereby is able to achieve larger roll rates

4.3. Load alleviation

In order to analyse the effects of a roll manoeuvre on the loads, the load quickness criterion is used. This parameter was originally developed by Pavel and Padfield [28].

$$Q_{load} = \frac{M_{XY_{peak}}(F_{XY_{peak}})/M_{XY_{trim}}(F_{XY_{trim}})}{\Delta\varphi} \quad (10)$$

Where M_{XY} (or F_{XY}) represents the magnitude of the longitudinal and lateral hub moments (or forces) combined (see equations 4 and 5) . It is essentially the amplification of the bending moment (or force) relative to its value in trim and accounts for the amplitude of the manoeuvre. As a consequence of the definition of the load quickness parameter, a line of constant load amplification has a '*one over x shape*' [29]. The hub forces and moment are filtered to remove the periodic components prior to computing the load quickness. The load quickness is displayed in Figure 18 and Figure 19.

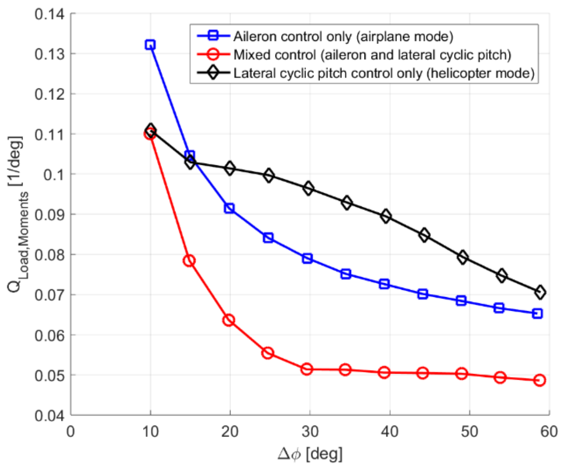

Figure 18: Comparison of load quickness (hub moments) for different control strategies

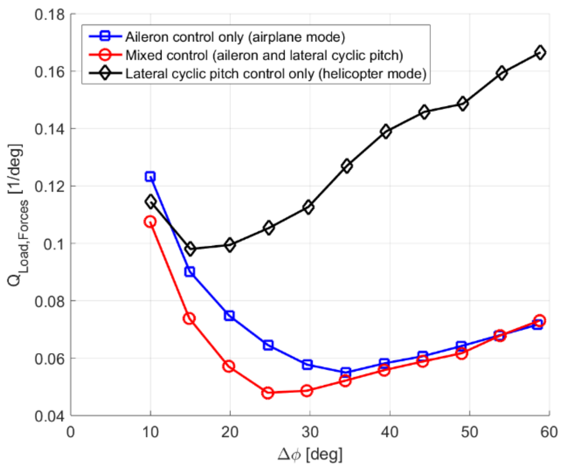

Figure 19: Comparison of load quickness (hub forces) for different control strategies

It can be observed that the mixed control strategy leads to the lowest hub moments for moderate amplitude roll attitude changes. In terms of the load quickness, hub moments are typically reduced in the range of 30 – 50%. With respect to the hub forces, the mixed control strategy also leads to the lowest loads. Compared to the control law which only uses the ailerons, the reduction in forces is small. However, there is a major reduction in hub forces compared to the situation where only lateral cyclic pitch control is used. For the largest amplitude attitude change, the forces in terms of the load quickness are reduced by 56%.

5. CONCLUSIONS & RECOMMENDATIONS

The potential benefits of using redundant controls on a compound helicopter for manoeuvre load alleviation whilst optimizing handling qualities were investigated. A nonlinear simulation model of a compound version of the Black Hawk was developed for this purpose

A trim analysis with the nonlinear simulation model demonstrated that the trim control strategy defined by the rotor RPM, horizontal stabilizer setting, compound thrust and aileron deflection, can have a profound effect on the hub loads (lateral and longitudinal forces and moments) both in terms of the mean value and the amplitude of the oscillatory loads.

Open loop responses to pulse inputs on the aileron and lateral cyclic pitch demonstrated that both controls can be used effectively for roll control but they have a profoundly different effect on the hub loads.

A set of roll attitude command, attitude hold control laws was developed for forward flight at 120 kts. Each control law had a different gearing ratio between the ailerons and lateral cyclic pitch. The gains of the control laws were optimized to achieve good time domain tracking performance and the best handling qualities. For all control laws, the effects on hub loads were compared.

It was demonstrated that by careful selection of the gearing ratio between aileron deflection and lateral cyclic pitch, the hub loads can be reduced in the order of 30% - 50% for moderate amplitude manoeuvres compared to a pure helicopter mode control or airplane mode control. At the same time, the predicted handling qualities (roll attitude quickness) can be improved due to the additional control power.

It is recommended that load alleviation objectives are included in the design of compound helicopter flight control laws for forward flight by exploiting the potential of redundant controls.

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