Post-Failure Control Reconfiguration on a High-Speed Lift-Offset Coaxial Helicopter

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ABSTRACT

An elastic blade trim model of a coaxial-pusher helicopter with aerodynamic interference between the rotors is described and validated against existing experimental data for coaxial rotor systems and helicopters. With the trim model in place, parametric sweeps of trim controls are performed to examine different allowable control settings in terms of the swashplate actuator positions on a generalized swashplate geometry at 3 different flight speeds representing a low speed, moderate speed, and high speed flight condition. The effective allowable ranges of locked-in-place positions are established for the 3 actuators on each swashplate, and explanations for the relative ranges are discussed. In low speed, differential moment variation between the rotors allows for actuator settings accounting for approximately 30% of the total range. In moderate and high speed these ranges change due to the moment balance between the rotor and aerosurfaces of the vehicle, with the aft actuator on each rotor trimmable over the entire allowable range, whereas the forward and lateral actuator on the two rotors have allowable ranges accounting for 40-60% and 20-25% of the total range, respectively.

NOTATION

LOS	Lift Offset
s_{aft}	Aft Swashplate Actuator Position (%)
s_{lat}	Lateral Swashplate Actuator Position (%)
s_{fwd}	Forward Swashplate Actuator Position (%)
T_{Prop}	Propeller Thrust (lb)
δ_e	Elevator Deflection (deg), positive TE down
δ_r	Rudder Deflection (deg), positive TE left
θ_0	Collective Pitch (deg)
θ_{Lon}	Longitudinal Pitch (deg)
θ_{Lat}	Lateral Pitch (deg)
$\Delta\theta_0$	Differential Collective Pitch (deg)
$\Delta\theta_{Lon}$	Differential Longitudinal Pitch (deg)
$\Delta\theta_{Lat}$	Differential Lateral Pitch (deg)
θ	Aircraft Pitch Attitude (deg), positive nose up
ϕ	Aircraft Roll Attitude (deg), positive roll right
Ω	Rotor Speed (RPM)

INTRODUCTION

High speed coaxial helicopters are poised to revolutionize the future of vertical flight. The ability of this platform to perform tasks beyond that of a traditional VTOL aircraft mission and extend the flight envelope into a high-speed regime is transformative for rotary wing vehicles. With the establishment of the Department of Defense Future Vertical Lift (FVL) initiative (Refs. 1, 2), coaxial-pusher aircraft have gained significant interest as these platforms are considered for the Future Attack Reconnaissance Aircraft (FARA) and the Future Long-Range Assault Aircraft (FLRAA). Through the Joint Multi-Role Technology Demonstrator (JMR-TD) program and FVL development, coaxial helicopters are being built and tested, continuously pushing the boundary of how fast, far, and long rotary wing vehicles can fly.

As with many advanced high-speed configurations, the coaxial platform has multiple redundant control effectors available in different flight regimes. This enables the aircraft to achieve non-unique trim states, which can be exploited for a number of different objectives, including load and vibration reduction, power optimization, and acoustic properties.

Jacobellis et al. (Ref. 3) utilized RCAS to explore parametric variation in two redundant controls (rotor speed and differential lateral cyclic) for the XH-59 aircraft and develop an understanding for the effect of different redundant control settings. The study identifies and analyzes both low power and low vibration conditions for the aircraft in high-speed flight conditions, highlighting the non-unique trim capabilities of the vehicle. Further trim analysis has been performed on a generic coaxial-pusher aircraft model at the University of Maryland with examination of trim optimization for a coaxial helicopter. Herrmann et al. (Refs. 4, 5) presented a study of a parametric sweep of propeller thrust and examine the effect on performance, noise, and fatigue of vehicle components. The authors then go on to develop a multiobjective optimization for the trim problem focusing on these same objectives.

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Concurrently, there has been parallel effort in the modeling of the flight dynamics of a coaxial helicopter. This poses a unique challenge because of the aerodynamic interference, the elastic dynamics of the stiff rotor system, as well as the larger flight envelope coaxial helicopters can achieve. The US Army Technology Development Directorate has worked on this modeling issue extensively, beginning with validation of predicted airframe dynamics of the X2 Technology™Demonstrator (Ref. 6). Recently, Berger et al. (Refs. 7, 8) have published work on a flight dynamics model of a generic coaxial-pusher helicopter, first analyzing the dynamic characteristics of the vehicle through linear systems analysis and examining potential implementation of a pseudo-inversion control allocation to account for the many control couplings that exist. The group went on to develop a flight control system for the generic coaxial-pusher model with CONDUIT and examine the handling qualities of the vehicle both through linear analysis and piloted simulation.

Control redundancy is not restricted to coaxial helicopters, other advanced high-speed configurations also possess more controls than are strictly required for trim and control, such as a thrust or lift compounded helicopter. Work done at Rensselaer by Reddinger and Gandhi explored parametric sweeps of trim controls for a compounded version of the UH-60 Black Hawk, identifying minimum power and vibration conditions for the aircraft at high speed (Ref. 9). Further work examined the potential use of redundant controls to tolerate a locked-in-place failure of a swashplate servo actuator (Ref. 10), where the authors identified potential tolerable ranges of actuator locked positions in trim. More recently the authors of the present study (Refs. 11, 12) continued this work by examining the flight dynamics of a vehicle with these locked swashplate servo failures. In this work, a UH-60 Black Hawk model derived from GenHel is used to examine the potential of using the stabilator as a redundant control to reconfigure the aircraft after a locking failure in the swashplate, demonstrating that it is possible to recover the aircraft with such a fault and also examining the effect of different control allocation of the swashplate on the vehicle handling qualities both pre- and post- actuator failure.

In the compound helicopter literature cited herein, both parametric variation of redundant controls for the optimization of some objective (power, vibration, etc.) and potential fault tolerance in different flight conditions are considered. There is no complimentary body of work to consider the coaxial helicopter's ability to reconfigure controls in the event of component failure. The present study seeks to fill this gap and investigate the potential for fault compensation in flight for a lift-offset coaxial helicopter by examining the interchangeability of controls at different points within the flight envelope, thereby identifying allowable fault cases for the vehicle.

APPROACH

The coaxial helicopter model used in this study is a 5,300 lb coaxial helicopter with a pusher-propeller, based off of Sikorsky's X2 Technology™Demonstrator (Fig. 1). Rotor geometry is taken from public information published by Bagai (Ref. 13), with other pertinent aircraft parameters taken from Blackwell and Millott (Ref. 14). Fuselage and tail aerodynamics are taken from the XV-15 simulation model (Ref. 15) and scaled appropriately. Table 1 gives a summary of the aircraft parameters implemented in the model.

Figure 1. Sikorsky X2 Technology™Demonstrator at the Udvar-Hazy Center in Chantilly, VA

Table 1. Coaxial Model Details

Aircraft	
Gross Weight	5,300 lb
Horizontal Tail Area	21 ft^2
Vertical Tail Area	15 ft^2
Rotor	
Radius	13.2 ft
N_b/Rotor	4
Hub Separation	14% R
Ω (Hover)	448 RPM
M_{tip} Limit	0.9
Pusher Prop	
Radius	3.3 ft (0.5 m)
N_b	6
σ	0.2
Ω	2,000 RPM

Rotor Aerodynamics

The rotor aerodynamic loads are modeled with Blade Element Theory along with a Pressure Potential Superposition Inflow Model (PPSIM, Ref. 16). Blade geometry (chord, twist, thickness distributions) is taken from Bagai (Ref. 13) and modern high speed airfoils found on Sikorsky's X2 Technology™Demonstrator are used along the span.

Rotor Dynamics

Blade dynamics are modeled using an elastic blade formulation with a Rayleigh-Ritz approximation of the natural bending modes of the blade. Two flap-wise bending modes are used in the approximation. Representative mass and stiffness properties are synthesized from publicly available information on the XH59-A, the generic coaxial-pusher model utilized in Ref. 17, as well as previous work from Jacobellis et al. (Ref. 18). These distributions of mass and flapwise stiffness are scaled to match the published blade natural frequencies in Ref. 14 as well as tip clearance data provided in Ref. 19.

Rotor Controls and Swashplate Representation

The rotor controls as defined in this study represent the inputs to the rotor head and do not contain any control phase angle that is typically seen to absorb the phase lag associated with rotor blade dynamics and aerodynamic interference effects. Note that the phase lag that would be included for the stiff coaxial rotor system would be substantially less than the classical 90 degrees found on a fully articulated rotor head.

For a typical rotor, there are 3 independent controls traditionally represented by a collective pitch as well as two cyclic inputs. In most helicopter control systems, these controls define the blade pitch at any point about the azimuth as

$$\theta(\psi) = \theta_0 + \theta_{1c}\cos\psi + \theta_{1s}\sin\psi, \tag{1}$$

where θ_0 is the collective and θ_{1c} and θ_{1s} are the one per revolution cosine and sine cyclic pitch inputs to the rotor. When a dual rotor system is considered, there now exist 6 independent controls to the rotor system, which can be represented as the 3 unique controls for each of the two rotor heads or some combination of controls as desired in the design of the flight controls.

For the purposes of this study, the coaxial rotor controls will be defined as follows in Table 2.

Table 2. Coaxial Rotor Controls

Control	Description
θ_0	Collective
θ_{lon}	Longitudinal
θ_{lat}	Lateral
$\Delta\theta_0$	Differential Collective
$\Delta\theta_{lon}$	Differential Longitudinal
$\Delta\theta_{lat}$	Differential Lateral

With these controls, the individual rotor pitch variation can be described as Eq. 2.

$$\begin{aligned} \theta_U(\psi_U) &= (\theta_0+\Delta\theta_0)+(\theta_{lon}+\Delta\theta_{lon})\cos\psi_U + \\ &\qquad (\theta_{lat}+\Delta\theta_{lat})\sin\psi_U, \\ \theta_L(\psi_L) &= (\theta_0-\Delta\theta_0)+(\theta_{lon}-\Delta\theta_{lon})\cos\psi_L - \\ &\qquad (\theta_{lat}-\Delta\theta_{lat})\sin\psi_L. \end{aligned} \tag{2}$$

With some rearranging, the rotor system controls can be defined in terms of the upper and lower rotor collective and cyclic inputs as:

$$\theta_0 = \frac{\theta_{0_U}+\theta_{0_L}}{2} \quad (3) \qquad \Delta\theta_0 = \frac{\theta_{0_U}-\theta_{0_L}}{2} \quad (6)$$

$$\theta_{lon} = \frac{\theta_{1c_U}+\theta_{1c_L}}{2} \quad (4) \qquad \Delta\theta_{lon} = \frac{\theta_{1c_U}-\theta_{1c_L}}{2} \quad (7)$$

$$\theta_{lat} = \frac{\theta_{1s_U}-\theta_{1s_L}}{2} \quad (5) \qquad \Delta\theta_{lat} = \frac{\theta_{1s_U}+\theta_{1s_L}}{2} \quad (8)$$

Another key component in the rotor controls is the swashplate geometry. To this end, a generic swashplate geometry is developed to analyze different flight conditions and potential limiting situations for the rotor system. The derivation is simple, requiring the minimum and maximum collective pitch allowable at the rotor head as well as the azimuthal positions of the swashplate servo actuators on the non-rotating swashplate.

First, consider the normalized throw of a servo actuator, that is $s \in [0,1]$. Note that if all actuators are in the minimum position, the blade pitch will by definition exist at the minimum allowable collective setting, it follows similarly for the maximum servo position and maximum collective setting. Defining this allowable collective range as $\theta_0 \in [\theta_{min}, \theta_{max}]$, it follows that at the azimuthal position of the i^{th} servo, the blade root pitch is

$$\theta(\psi_i) = (\theta_{max}-\theta_{min})s + \theta_{min}. \tag{9}$$

From here, the relation to the rotor head controls (θ_0, θ_{1c}, and θ_{1s}) is given by

$$\theta(\psi_i) = \theta_0 + \theta_{1c}\cos\psi_i + \theta_{1s}\sin\psi_i. \tag{10}$$

Equating the two expressions (Eqs. 9 and 10) for the local blade root pitch gives the linear-affine mapping from actuator to rotor head controls as

$$\begin{aligned} T_{\theta/s}\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} + b_{\theta/s} &= T_\theta \begin{bmatrix} \theta_0 \\ \theta_{1c} \\ \theta_{1s} \end{bmatrix}, \\ T_{\theta/s} &= (\theta_{max}-\theta_{min})I_3, \\ b_{\theta/s} &= \begin{bmatrix} \theta_{min} & \theta_{min} & \theta_{min} \end{bmatrix}^T, \\ T_\theta &= \begin{bmatrix} 1 & \cos\psi_1 & \sin\psi_1 \\ 1 & \cos\psi_2 & \sin\psi_2 \\ 1 & \cos\psi_3 & \sin\psi_3 \end{bmatrix}. \end{aligned} \tag{11}$$

Note that this is a generalized and simple representation of a swashplate, in reality swashplate geometry is more complex with other limitations defining the relation between actuator position and rotor head controls. This relation, however, allows for extraction of the general relation between actuators (in certain positions) and rotor head controls, which can assist in identifying flight conditions where actuators may be at relatively extreme positions. The ability to translate pitch control to actuator position can also allow for the identification of ranges of positions that exist throughout large portions of the flight envelope, which can imply aircraft trim for a locked swashplate actuator.

For the present study, the swashplate actuators are assumed to be located at 0, 90, and 180° in the appropriate swashplate azimuthal coordinate. These actuators are consequently labeled s_{aft}, s_{lat}, and s_{fwd} for each rotor. The results that follow assume an allowable collective setting range from -5 to 15 degrees on each rotor, which results in a $\pm 10°$ range in θ_{1c} and $\pm 20°$ in θ_{1s} according to the defined model.

Model Validation

The application of PPSIM within the implemented BET framework was validated against the Harrington rotor 1 (tapered) data (Ref. 20) as well as experimental measurement from the University of Texas at Austin (Ref. 21). Figure 2 gives validation of the coaxial rotor model in hover, showing good agreement between the current model prediction and the Harrington experiment. Further, Fig. 3 gives good validation again in hover against the UT Austin test data, but this experimental data also extends the model validation to advance ratios above 0.5 (Figs. 4 and 5). Note that in Figs. 4 and 5, the markers represent experimental data, while the lines represent the model prediction.

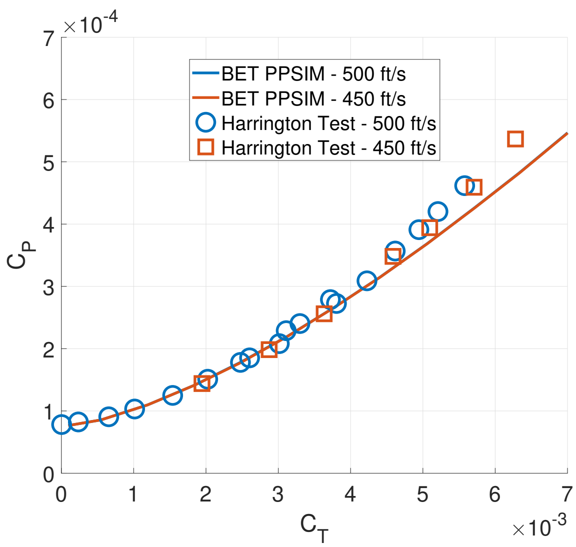

Figure 2. Harrington Rotor 1 Validation - Hover (Ref. 20)

With the rotor model validated, the assembly of the aircraft components for the representative X2TD model was also considered. This is done in 2 parts, beginning with the blade mass and stiffness properties. The blade natural frequencies are given in Blackwell and Millott (Ref. 14), which can be used to validate the modal characteristics of the modeled blade. Figure 6 shows that the estimated natural frequencies for the first two out of plane bending modes match well for the typical rotor speeds during operation (model prediction is the colored dashed line, test data is the colored solid line).

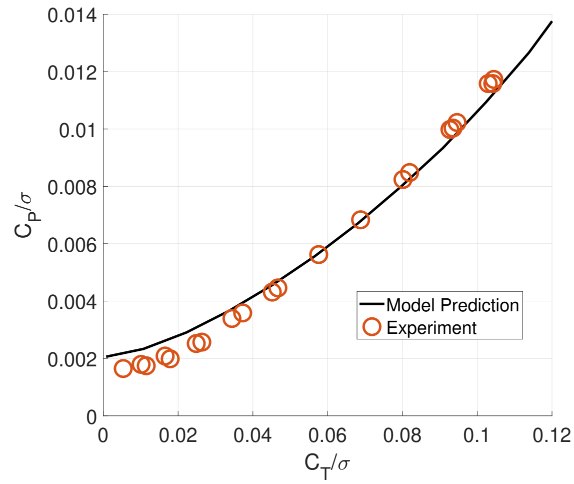

Figure 3. UT Austin Rotor Validation - Hover (Ref. 21)

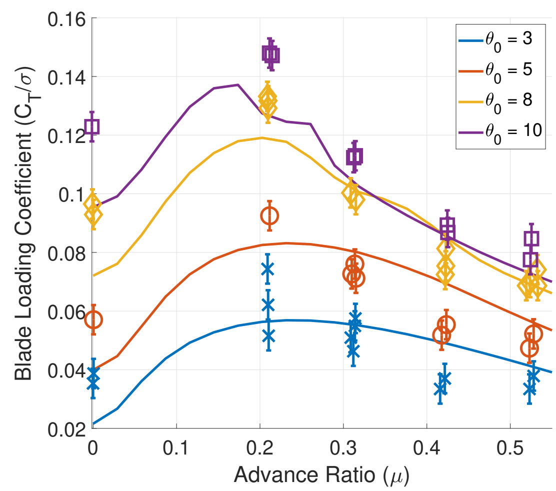

Figure 4. UT Austin Blade Loading vs Advance Ratio (Ref. 21)

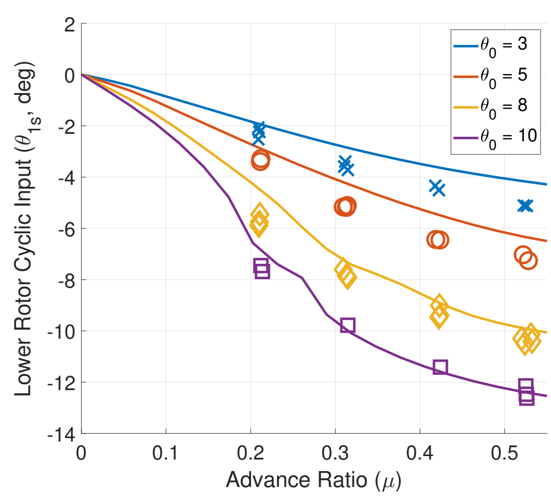

Figure 5. UT Austin Lower Lateral Cyclic Pitch vs Advance Ratio (LOS =0) (Ref. 21)

From here, the elastic blade model was implemented into the full aircraft trim model and a velocity sweep was completed. Predictions of rotor and propeller power, as well as lift offset and tip clearance are compared to the published flight test data for the X2 provided by Walsh (Ref. 19). Figure 7 shows good validation of the aircraft model, with slight under prediction of the rotor power at low speed likely due to deficiency in the rotor interference model as well as rotor wake impingement on different aircraft surfaces. Figures 8 and 9 then validate the aerodynamic prediction and structural model for the rotor system through the predicted lift offset and tip clearance.

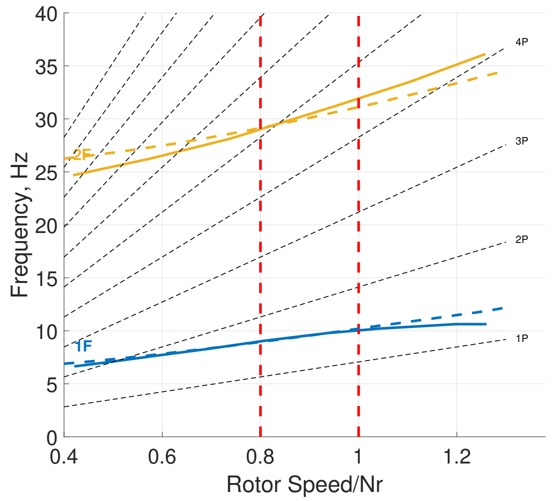

Figure 6. Bending Mode Natural Frequencies (Ref. 14)

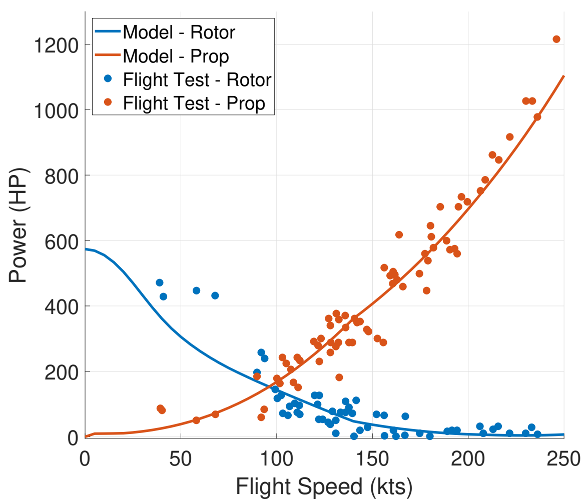

Figure 7. X2 Rotor and Prop Power (Ref. 19)

Paper Overview

With the model in place and validated, the present study seeks to examine the use of redundant controls in different flight regimes for the notional X2 aircraft model developed. This

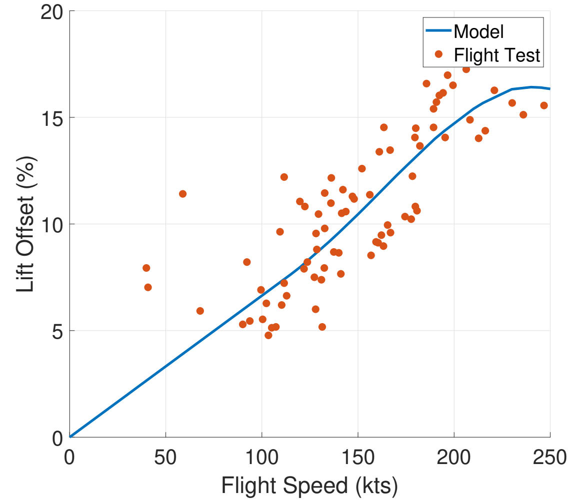

Figure 8. X2 Lift Offset (Ref. 19)

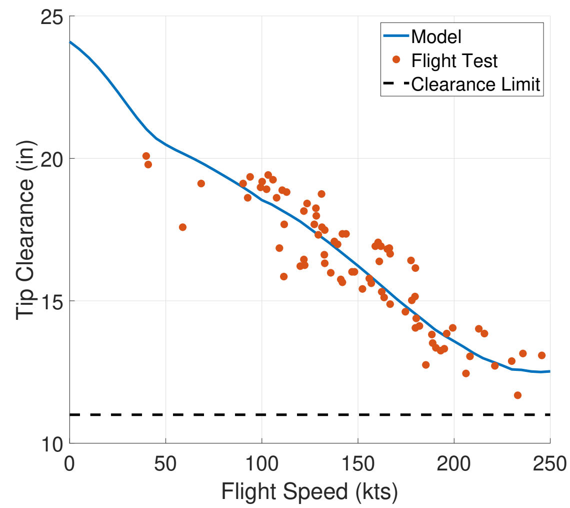

Figure 9. X2 Tip Clearance (Ref. 19)

is done by running a nominal trim across different airspeeds ranging from hover to 250 kts, which is defined by a prescribed lift offset and pitch attitude at each flight speed. It should be noted that longitudinal lift offset is nominally held at 0%, lateral lift offset is prescribed to follow the blue curve in Fig. 8, and the pitch attitude follows a schedule defined as 0° from 0-20 kts, linearly increasing from 0 to 3.75° nose up between 20-140 kts, then remaining at 3.75° above 140 kts. Also, an elevator is added to the X2 model and scheduled in order to reduce the rotor hub pitching moment in forward flight.

Three regimes are then chosen for analysis, low speed (20 kts), moderate speed (120 kts), and high speed (220 kts). At each speed, controls are parametrically varied including the pitch attitude, elevator deflection, as well as the lateral and longitudinal lift offset of the rotor system in order to see the allowable range of trim inputs as well as common control settings in different conditions, which can indicate an ability to trim multiple flight states with a locked flight control.

RESULTS

The parametric sweeps in the present study are performed in two sets – a two dimensional sweep of vehicle pitch attitude and elevator setting as well as a two dimensional sweep of lateral and longitudinal lift offset of the rotor system. This is designed to modulate the vehicle pitching moment distribution as well as the differential roll and pitch moment carried at the rotor hub to examine the different control configurations the helicopter can trim in. Lateral moment variation is more difficult to parametrically vary due to the lack of redundant lateral effectors on the aircraft. This results section will present and analyze these parametric variations at the different speeds, then present high level results indicating similar control settings across the different flight regimes.

Trim sweeps of pitch attitude and elevator setting hold the lateral and longitudinal lift offsets constant (with longitudinal lift offset at zero and lateral lift offset as shown in Fig. 8), conversely trim sweeps of longitudinal and lateral lift offset hold the pitch attitude and elevator setting at their nominal condition, which will be indicated in the discussion. The rotor speed is defined such that the tip mach number does not exceed 0.9, and is only different from the value in Table 1 at the high speed (220 kt) case.

LOW SPEED

The low speed case considered is trimmed primarily with the rotor controls, namely collective (θ_0), longitudinal (θ_{lon}), lateral (θ_{lat}), and differential collective ($\Delta\theta_0$). These settings for nominal trim are provided in Table 3, along with redundant control settings including the elevator (scheduled), rudder (inactive at low speed), differential longitudinal (trimmed for zero longitudinal lift offset), differential lateral (trimmed for lift offset schedule), and rotor speed (scheduled). Note that pitch attitude is set at zero and the propeller thrust is determined to satisfy trim.

Table 3. Low Speed Trim Controls

Active Trim Controls							
θ_0	θ_{lon}	θ_{lat}	$\Delta\theta_0$	T_{prop}	ϕ	$\Delta\theta_{lon}$	$\Delta\theta_{lat}$
8.5°	2.6°	0°	-0.2°	15.7 lb	0°	-0.2°	-0.8°
Prescribed Controls and Lift Offset							
θ	δ_e	δ_r	Ω		Lat.	Long.	
0°	0°	0°	448 RPM		1.3%	0%	

Pitch and Elevator Sweep

As expected in low speed flight, variation of aerosurfaces (elevator and rudder) has no significant effect on the aircraft trim. The pitch attitude of the vehicle has more impact on the vehicle trim than the elevator setting, though this is largely due to the change it creates in the aerodynamic environment of the rotor system and is still a small effect. Consider the variation in collective pitch and longitudinal input to the rotor system, given in Fig. 10.

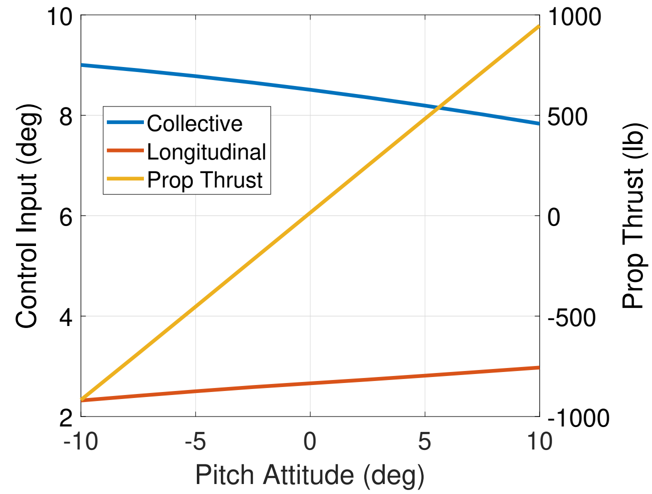

Figure 10. Trim Control Variation, Low Speed Pitch and Elevator Sweep

Note that the collective and longitudinal controls vary approximately 1 degree over the entire pitch attitude range. This indicates that the actuator settings for these swashplates will not change significantly either under these conditions. Lateral input (not shown) changes even less, as there is virtually zero change in the lateral moment on the vehicle with the exception of some small changes in the side forces of the rotors acting at their respective hubs. Also of note is the propeller thrust (right axis), which highlights the ability of the vehicle to trim nose up or nose down as the thrust output is varied to carry more or less of the vehicle weight.

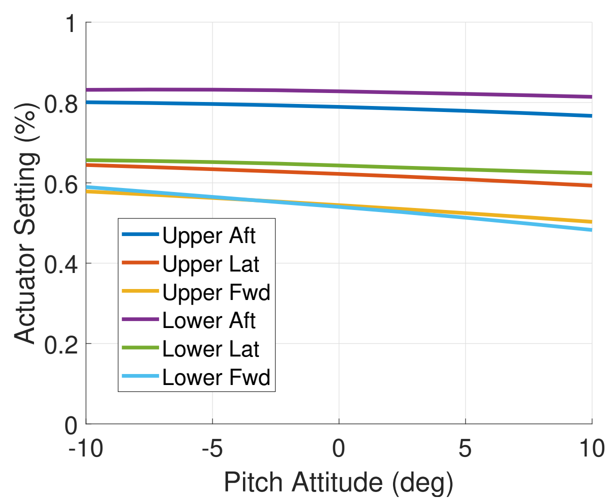

Figure 11. Swashplate Actuator Variation, Low Speed Pitch and Elevator Sweep

Examining the swashplate actuators for the two rotors (lower rotor will be simply shifted upward slightly from the differential collective input) in Fig. 11, the range of actuator positions is approximately 5-10% of the total throw. This range could expand slightly by increasing the range of the parametric sweep but clearly, for a nominal trim holding the differential moments to near zero condition, the allowable control ranges are small. This is typical for a helicopter near hover (Refs. 10, 11), as the rotor is the primary force and moment source for the vehicle.

An interesting feature highlighted in Fig. 11 is the relationship among the swashplate actuators for the pitch attitude variation. As intuition would dictate for a coaxial rotor system, the two rotors operate in a similar control setting, with some differences at low speed due to the aerodynamic interference. The line pairings in Fig. 11 are the aft, lateral, and forward actuators on each swashplate. This trend exists for all of the pitch attitude and elevator control sweeps conducted in the present study.

Lift Offset Sweep

On a single main rotor helicopter, the rotor generates forces and moments that are balanced by other components on the vehicle (tail rotor, aerosurfaces at sufficient dynamic pressure, etc.). However, because the coaxial helicopter has two rotors, a force or moment generated by one rotor can be compensated by the other. This creates a differential moment at the rotor shafts, which results in no body acceleration but can pose an issue in bending loads and tip clearance limits. The unique ability to create opposing force and moment between the two rotors can enable the aircraft to tolerate an atypical locked position of a swashplate actuator and potentially expand the allowable range of failed positions. For the following low speed results, both longitudinal and lateral lift offset are varied $\pm 20\%$ from the nominal trim.

The most significant control changes with a parametric variation of lift offset generally come in the differential controls, as expected. The differential longitudinal and differential lateral inputs are given in Figs. 12 and 13.

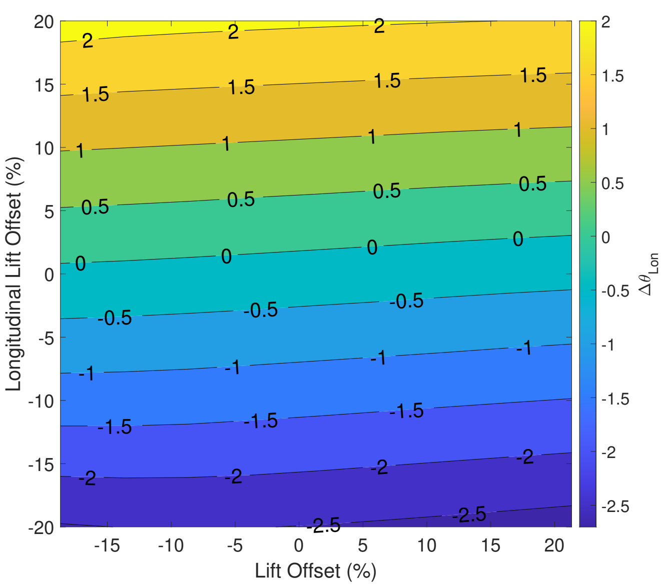

Figure 12. Differential Longitudinal Variation, Low Speed LOS Sweep

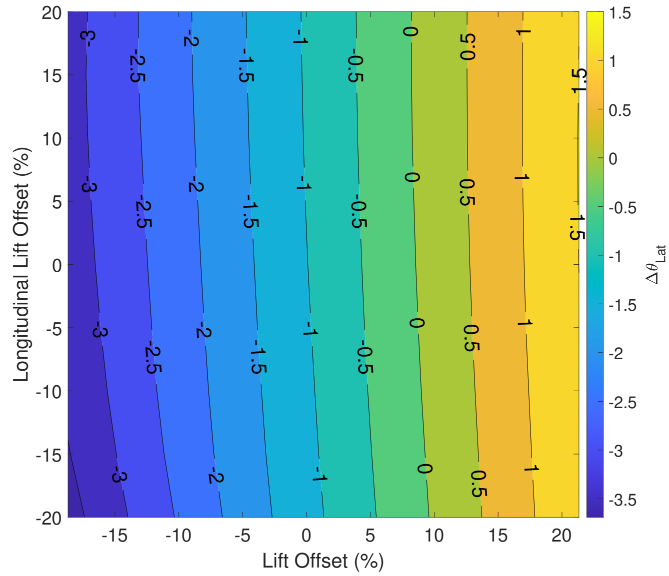

Figure 13. Differential Lateral Variation, Low Speed LOS Sweep

As expected, these contours are largely horizontal and vertical, respectively. Also worth noting is the total range of values taken on these figures, which are both around 5°, is notably larger than the range of controls in the pitch attitude sweep.

Along with the differential controls, the collective and yaw control ($\Delta\theta_0$ or δ_r) will change to account for the coupling in the differential inputs. One of the more significant impacts, especially in the differential lateral, is the loss of thrust coming from driving the center of lift inboard on the advancing blade. This will typically require an increase in the collective pitch to recover the lost thrust, but at 20 kts, the dynamic pressure asymmetry that drives this overall loss of thrust is small and the collective setting (not shown) varies approximately 1 degree across the parametric sweep. Another effect that is typically seen is a torque imbalance from use of differential longitudinal, where the side force change from different longitudinal loading and induced flow distributions result in a net torque depending on the application of $\Delta\theta_{lon}$. These variations will be shown and discussed in more detail at higher speeds, where the coupling in rotor controls is more significant.

Consider the upper rotor forward actuator, shown in Fig. 14. When pitch attitude was swept, Fig. 11 indicated a trimmable range of less than 10% of the total throw. Now, with differential moments allowed, the trimmable range expands to about 60% of the total throw. The expansion of the cyclic inputs to each rotor expands the range of actuator positions that the aircraft can now trim in. Although not shown, note that the other actuator positions also exhibit trimmable ranges over 50-60% of the total throw. The overall ranges of allowable actuator positions will be provided at the end of the results section.

In contrast to the pitch attitude sweep, a lift offset sweep results in opposing trends between the upper and lower swashplates in order to generate opposing moments at each rotor hub. Consider the lower rotor forward actuator, given in Fig. 15.

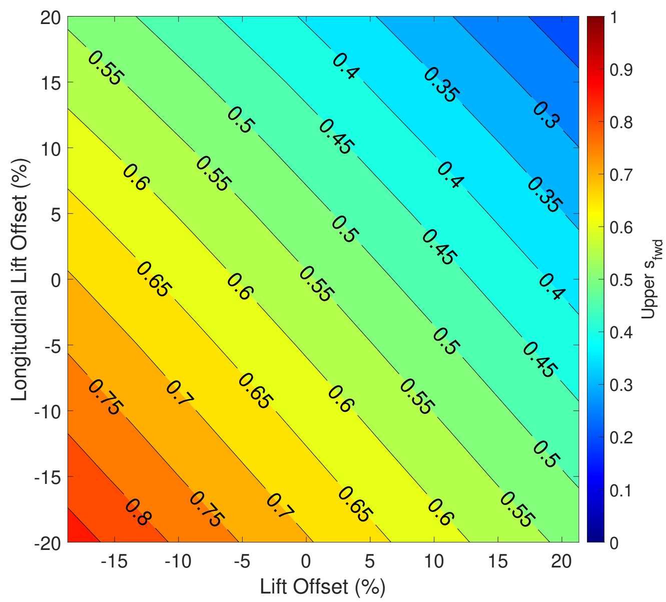

Figure 14. Upper Rotor Forward Actuator Variation, Low Speed LOS Sweep

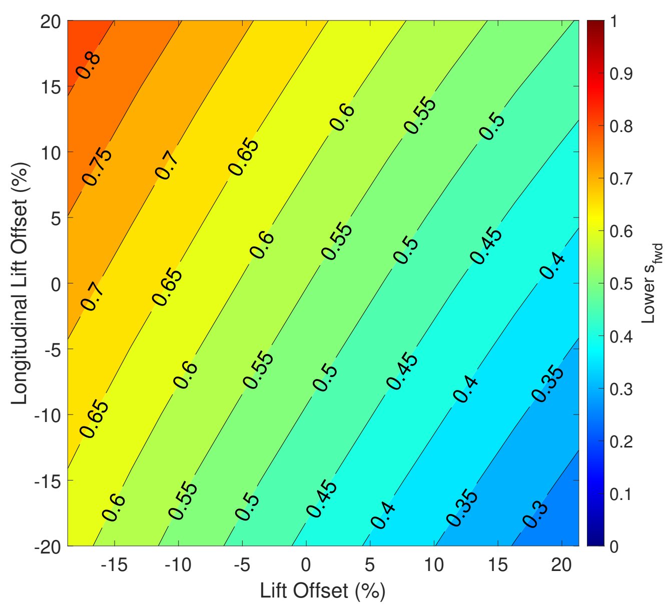

Figure 15. Lower Rotor Forward Actuator Variation, Low Speed LOS Sweep

The ranges in Figs. 14 and 15 are nearly identical, but the trend with longitudinal lift offset is flipped. This is because as the longitudinal lift offset is varied the upper and lower rotor need to produce opposite pitching moments in order to maintain trim, which requires the forward (and by extension aft) actuators on each swashplate to move in opposite directions. The trend flip does not occur for the lateral lift offset because of the swashplate actuator positions. That is, the same motion of the forward (or aft) actuator naturally produces the opposing roll moment required by the desired lateral lift offset.

Differential moments at the shaft don't generate body accelerations, but they generally reduce the tip clearance between the two rotors as the differential moment causes a differential flapping on the two rotors. The rotor tip clearance is given in Fig. 16, along with the published flight test tip clearance limit (Ref. 19) of 11 inches, given by the red dotted line.

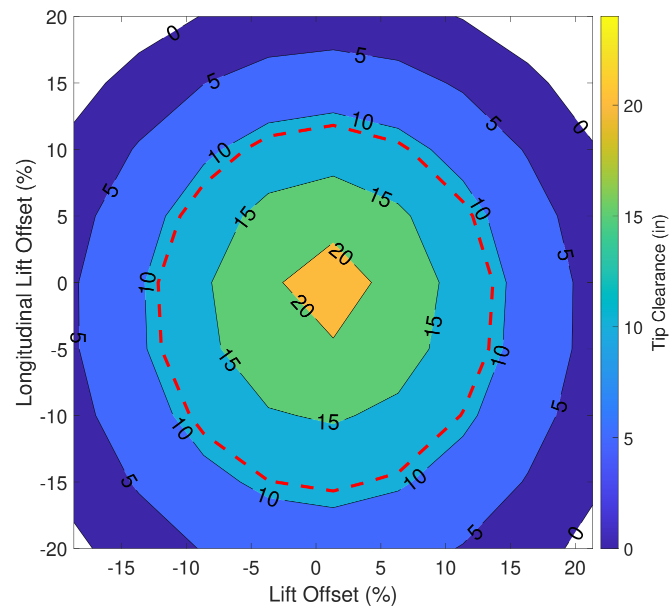

Figure 16. Tip Clearance Variation, Low Speed LOS Sweep

As is expected, the tip clearance contours are largely circular. The clear implication of this figure is that although the aircraft is trimmable over a larger control range than it was for just the pitch attitude and elevator sweep, the tip clearance limitation becomes important when investigating differential moment variation. If the tip clearance limit is held at the 11 inch value, then the previously noted 60% trimmable range of the upper rotor forward actuator reduces to approximately 30% of the total throw. However, in a situation where a failure occurs, the tip clearance limit may be ignored or reduced such that trim is achievable over a wider range of actuator settings.

MODERATE SPEED

At moderate speed (120 kts), aircraft trim is accomplished differently than in the low speed case (Table 4).

Table 4. Moderate Speed Trim Controls

Active Trim Controls							
θ_0	θ_{lon}	θ_{lat}	δ_r	T_{prop}	ϕ	$\Delta\theta_{lon}$	$\Delta\theta_{lat}$
2.9°	3.6°	-0.2°	0.1°	537 lb	0°	-0.2°	-2.5°
Prescribed Controls and Lift Offset							
θ	δ_e	$\Delta\theta_0$	Ω	Lat.	Long.		
3.125°	-4.2°	0°	448 RPM	8%	0%		

According to Walsh (Ref. 19), the X2 was flown nose up between 2-5° above 120 kts, and so a pitch attitude schedule is introduced into the trim that takes the aircraft from nose level at hover and low speed up to approximately 4 degrees nose up after 140 kts. Above 60 kts, differential collective is washed out because it no longer is effective, and the rudder is used for directional authority. The lateral lift offset, following Fig. 8, is approximately 8% in the nominal condition.

Pitch and Elevator Sweep

Unlike the 20 kt condition, at 120 kts the dynamic pressure on the aerosurfaces of the vehicle is significant. Therefore, variation in both pitch attitude and elevator setting can accommodate larger changes in trim controls and maintain the prescribed condition relative to the low speed case. This change is largely brought about by the different loading on the horizontal tail and fuselage, which result in different thrust and pitching moment being required from the rotor system and consequently result in variation in the collective and longitudinal settings (Figs. 17 and 18).

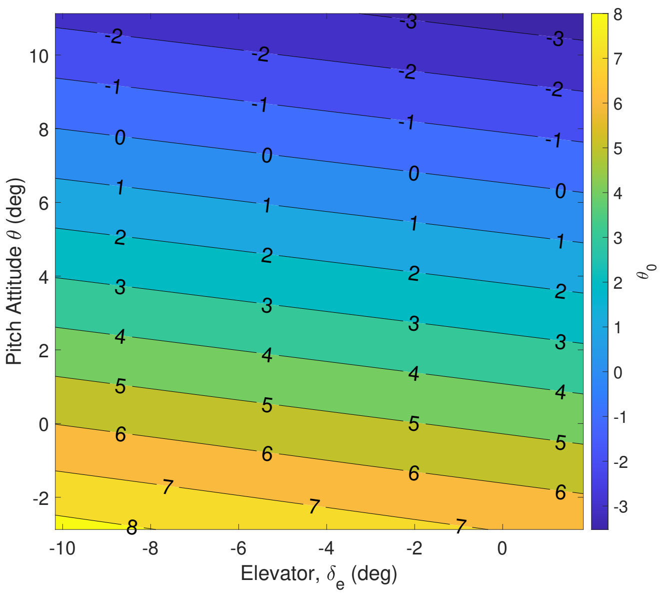

Figure 17. Collective Pitch Variation, Moderate Speed Pitch and Elevator Sweep

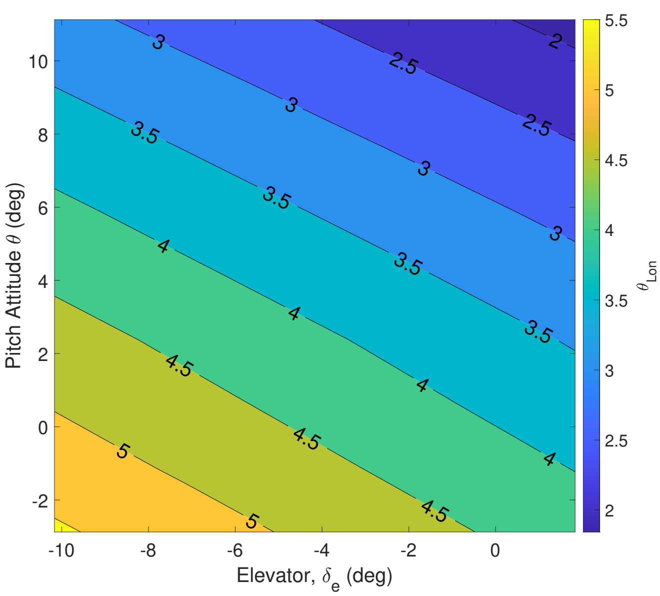

Figure 18. Longitudinal Pitch Variation, Moderate Speed Pitch and Elevator Sweep

These contours represent a larger set of allowable controls for trim (relative to low speed), which is expected because of the larger range of external loads coming from the fuselage and other aerosurfaces on the vehicle. It should be noted that for all points within this parametric sweep, lateral and longitudinal lift offset is maintained, which generally implies that the rotor tip clearance is maintained. Therefore, the limitations when examining the trim of the vehicle exist in the performance limits and geometric control limits.

Looking again at the upper rotor forward servo positions (Fig. 19), it is clear that the actuator range has expanded compared to the low speed case, from roughly 8% of the total range to approximately 37%. However, the range that exists in this sweep is exclusive of the values that were found for the 20 kt case. That is, Fig. 11 indicates a trimmable range of forward actuator position between 48 and 58%, where Fig. 19 indicates a range between 0 and 36%, due to the low collective setting and relatively high longitudinal input. This suggests that a locked failure in the forward actuator would need to be dealt with differently in the two flight speeds.

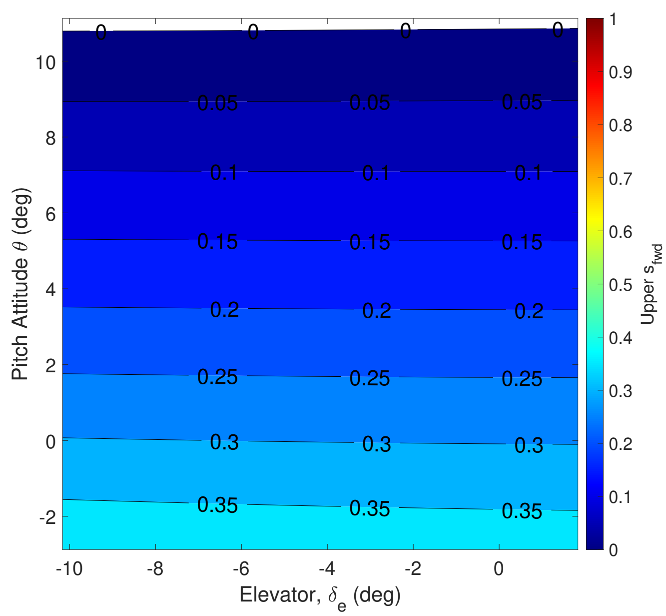

Figure 19. Upper Rotor Forward Actuator Variation, Moderate Speed Pitch and Elevator Sweep

The aft actuator on the upper rotor shows a different result, however. Because of the high longitudinal setting, this actuator needs to be raised substantially. Also, because the trim space involves a several degree change in both collective and longitudinal, where both controls increase as pitch attitude and elevator setting decrease, the aft actuator turns out to be the most active on the swashplate (Fig. 20), with a trimmable range of 20 to 100%.

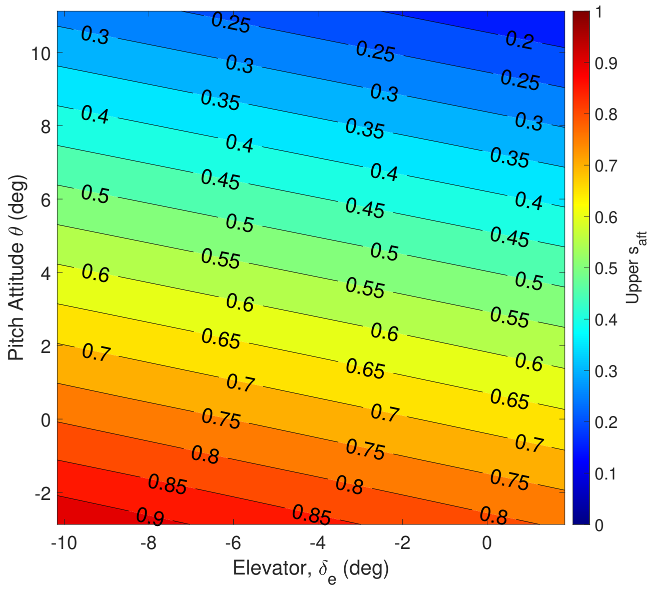

Figure 20. Upper Rotor Aft Actuator Variation, Moderate Speed Pitch and Elevator Sweep

Lift Offset Sweep

Similar to the low speed case, longitudinal and lateral lift offset can be varied from the nominal condition of 0 and 8%, respectively. Unlike the low speed case, however, the variation in these lift offset parameters and consequentially the differential cyclic inputs results in significant coupled responses. As mentioned in the low speed section, these off-axis effects largely manifest in thrust and torque imbalance. The differential controls follow similarly to Figs. 12 and 13 for the 120 kt case ($\Delta\theta_{lon} \in [-1.5, 1.25]^\circ$, $\Delta\theta_{lat} \in [-4.5, -0.5]^\circ$), and are not shown here. However, the variation in collective (Fig. 21) and rudder (Fig. 22) are given to demonstrate the behavior of the coaxial rotor system in this flight regime.

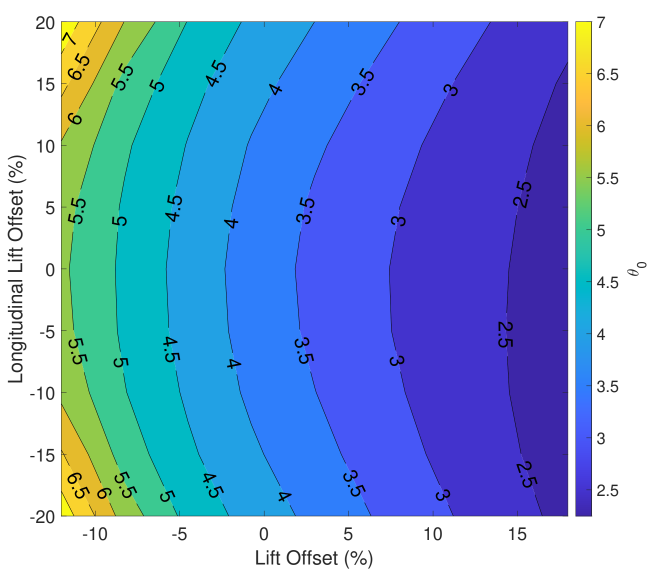

Figure 21. Collective Pitch Variation, Moderate Speed LOS Sweep

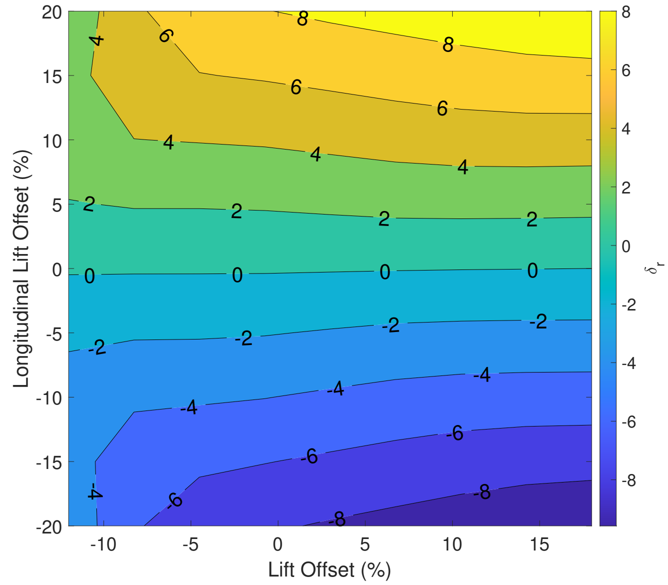

Figure 22. Rudder Variation, Moderate Speed LOS Sweep

As discussed previously, differential lateral tends to change the net thrust of the rotor system, so as the lateral lift offset (and therefore differential lateral input) changes, so too does the collective input to the vehicle. In a similar fashion, differential longitudinal changes the torque balance of the two rotors, so as longitudinal lift offset changes, the rudder setting changes as well.

The rotor tip clearance is given in Fig. 23 along with the tip clearance limit given by the dashed red line.

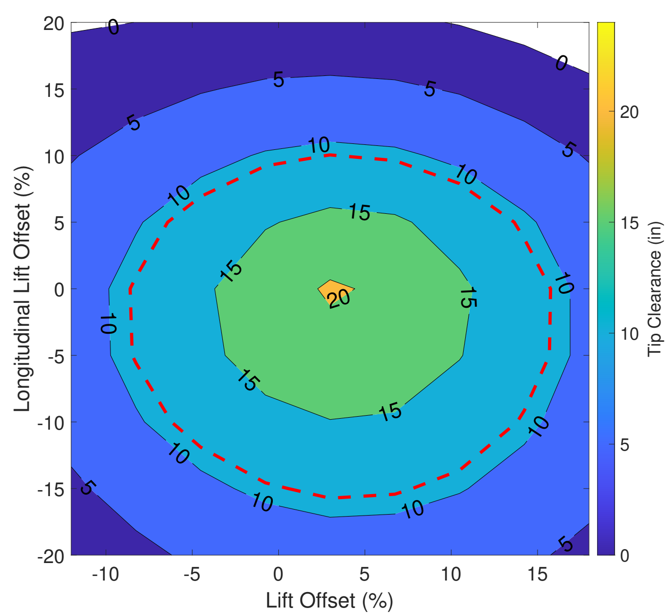

Figure 23. Tip Clearance Variation, Moderate Speed LOS Sweep

Note that the peak in the contours no longer occurs at (0,0) due to the presence of a net roll moment being carried by the rotors to account for the prop torque. The forward actuator position is also given (Fig. 24) for this lift offset sweep for comparison to the pitch attitude and elevator sweep. Note that the range of trim solutions now contains 5-70% of the total throw, though applying the tip clearance limit realistically brings this range to 15-40%. Note that this range is representative of the sweep considered, but may expand if the entire trim space is considered. This is an improvement over the results in the pitch sweep, however, because now there is some commonality in the contour values at low speed (Fig. 14) and moderate speed range (Fig. 24), indicating common trim between the two cases.

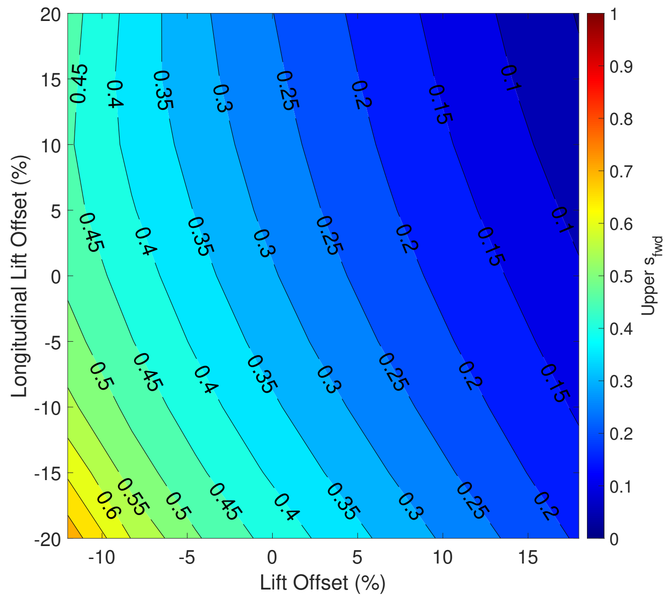

Figure 24. Upper Rotor Forward Actuator Variation, Moderate Speed LOS Sweep

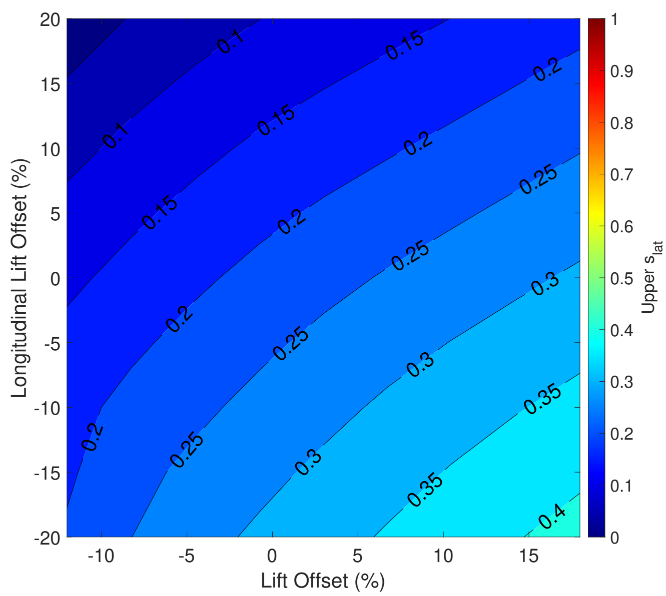

Figure 25. Upper Rotor Lateral Actuator Variation, Moderate Speed LOS Sweep

Another note from the lift offset sweep is the variation in lateral actuator position (Fig. 25). Although not shown, the pitch attitude and elevator sweep at moderate speed allowed a lateral actuator trim range of approximately 15 to 35% because of the lateral lift offset trim. In the lift offset sweep at moderate speed, this range (Fig. 25) expands, now covering 5 through 40% without considering tip clearance limits (which reduces the range to 15 to 35%).

HIGH SPEED

At high speed (220 kts), the aircraft is quite sensitive to changes in its operating condition. The dynamic pressure on the tail is large, the free stream wash is large enough to overcome the induced flow of the rotor, and the advance ratio is greater than 0.6 because of the slowed rotor speed. These factors make trim more difficult in this regime. The trim controls are given in Table 5. Note that the lift offset is approximately 16% in this condition.

Table 5. High Speed Trim Controls

Active Trim Controls							
θ_0	θ_{lon}	θ_{lat}	δ_r	T_{prop}	ϕ	$\Delta\theta_{lon}$	$\Delta\theta_{lat}$
0.3°	4°	-0.4°	0.6°	1,113 lb	-1.3°	-0.6°	-2.1°
Prescribed Controls and Lift Offset							
θ	δ_e	$\Delta\theta_0$	Ω	Lat.	Long.		
3.75°	-5°	0°	444 RPM	16%	0%		

Pitch and Elevator Sweep

As mentioned previously, the tail and other aerosurfaces are very sensitive to changes in pitch attitude and surface deflections at high speed. This leads to larger outputs from the tail and more compensation required from the rotor system. Figures 26 and 27 give the collective and longitudinal control for the rotor system over a pitch attitude and elevator setting sweep.

At high speed, increasing the pitch attitude of the vehicle changes the net wash going through the rotor disks. The nominal trim collective is around 0°, going more nose up requires even smaller collective input as a result of both larger upwash through the disk and larger lift from the tail and fuselage. Conversely, as the aircraft goes more nose down, the free stream component along the vertical shaft axis decreases, which (along with reduced fuselage and tail lift) in turn leads to a larger required collective pitch setting. Note that the top right and bottom left of these contours contain the assumed maximum and minimum collective settings indicated previously.

Compared to the previous two sweeps of the same trim controls, these contours show a substantially larger change in the rotor controls. As a result, the range of actuator positions is also changing substantially. Again, consider the upper rotor forward and aft actuators (Figs. 28 and 29).

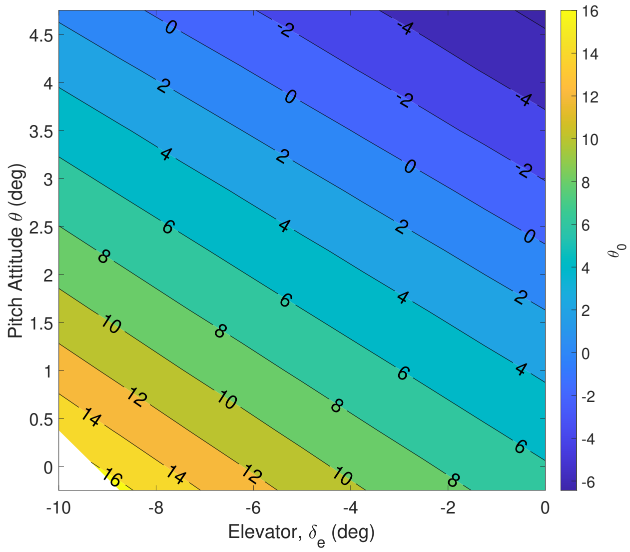

Figure 26. Collective Pitch Variation, High Speed Pitch and Elevator Sweep

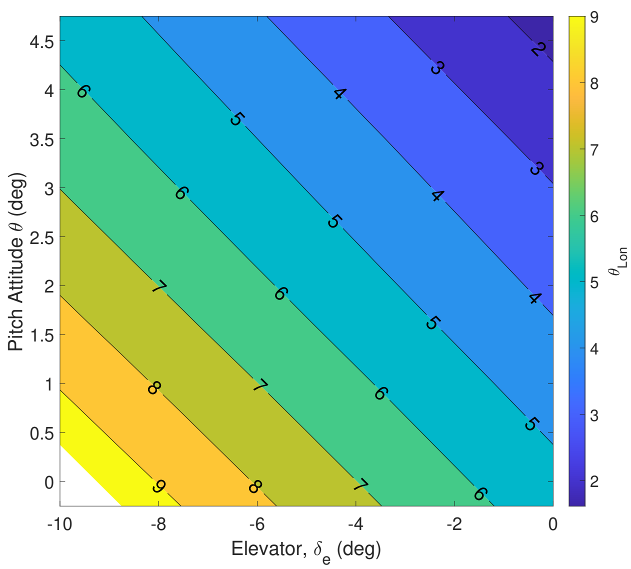

Figure 27. Longitudinal Pitch Variation, High Speed Pitch and Elevator Sweep

Note that both actuators experience their minimum setting in the top right corner of the contours, where collective and longitudinal settings are both lowest. The aft actuator here actually can be trimmed at the full range of settings according to the provided swashplate geometry, while the forward actuator can trim over more than half of its allowable range (due to the low collective setting at high speed). The high density of the contours suggests that the aircraft is quite sensitive to the changes along both axes, which again is expected with high dynamic pressure. Note that the lateral actuator (not shown) doesn't change much (variation from 10-20% of total throw), as the lateral moment balance is largely unaffected.

Another noteworthy result for the pitch attitude and elevator sweep is the change in differential lateral required to maintain the scheduled lateral lift offset, shown in Fig. 30. When the

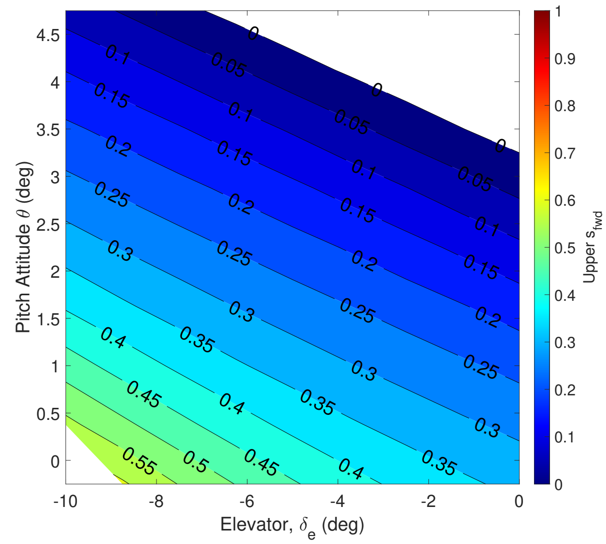

Figure 28. Upper Rotor Forward Actuator Variation, High Speed Pitch and Elevator Sweep

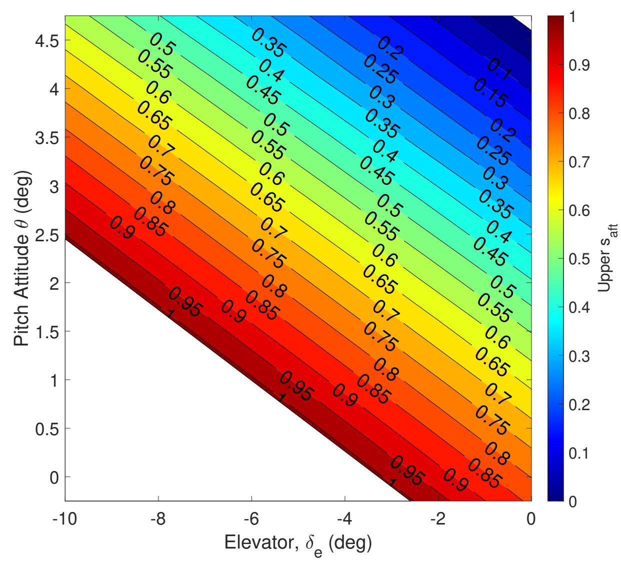

Figure 29. Upper Rotor Aft Actuator Variation, High Speed Pitch and Elevator Sweep

aircraft is more nose-level, the fuselage and tail lift decreases, which requires an increase in the collective setting to balance. This increase in collective generally increases the advancing side blade lift, which tends to drive lateral lift offset larger and negative differential lateral is required to keep this value at the desired level.

Lift Offset Sweep

The lift offset sweep at high speed is very similar to the moderate speed case. This is an intuitive result, as the rotor controls required to trim (Table 5) is quite similar to the moderate speed trim (Table 4) with the exception of the collective pitch setting and lift offset. The tip clearance is given in Fig, 31, with the 11 inch tip clearance limit (dashed red line).

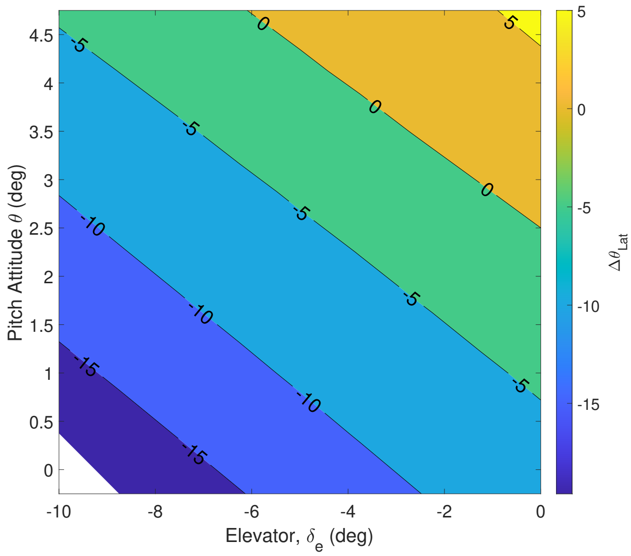

Figure 30. Differential Lateral Variation, High Speed Pitch and Elevator Sweep

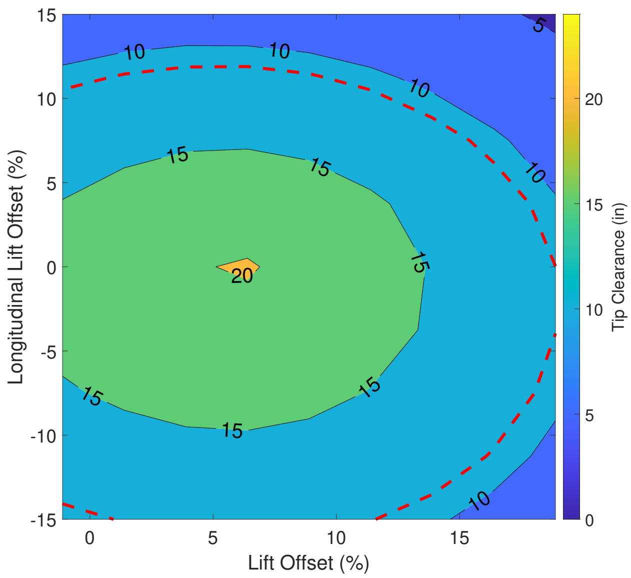

Figure 31. Tip Clearance Variation, High Speed LOS Sweep

The tip clearance behavior is similar to both the low and moderate speed case, however the maximum is now located at 0% longitudinal and approximately 5% lateral lift offset. This repositioning pushes the maximum allowable lateral lift offset out closer to 20% and is due to the non-zero roll moment carried by the rotors to balance the propeller torque. Also worth noting is that because lift offset is a value normalized by total rotor thrust, when the rotor thrust decreases (as it does at high speed due to the increased fuselage and tail lift), the dimensional differential moment being carried by the rotor system is less at the same lift offset value. As a result, the actual bending moment for the blade is roughly the same for approximately 20% lateral lift offset corresponding to the tip clearance limit in Fig. 31 as it is for the maximum lateral lift offset for the low speed case in Fig. 16.

The upper rotor forward and lateral actuator positions for the lift offset sweep are given in Figs. 32 and 33, respectively. Compared to the moderate speed case, the ranges are quite similar for both actuators. However, unlike the low speed case, these ranges do not represent any significant improvement over the pitch and elevator sweep ranges of actuator setting. It should be noted, however, that these ranges would generally shift depending largely on the pitch attitude of the vehicle (as collective and longitudinal setting change) as well as the elevator setting. Slowing the rotor further would also tend to increase all of these actuator positions (by increasing the required collective pitch setting), and could be used to keep the working state of the actuators closer to that of the hover/low speed condition.

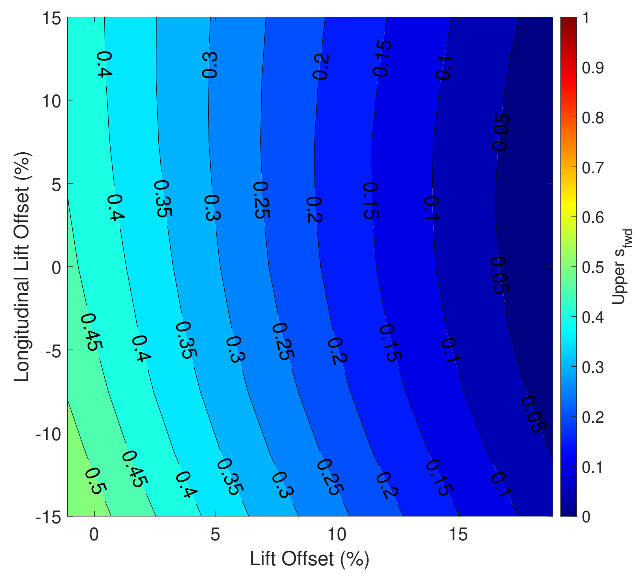

Figure 32. Upper Rotor Forward Actuator Variation, High Speed LOS Sweep

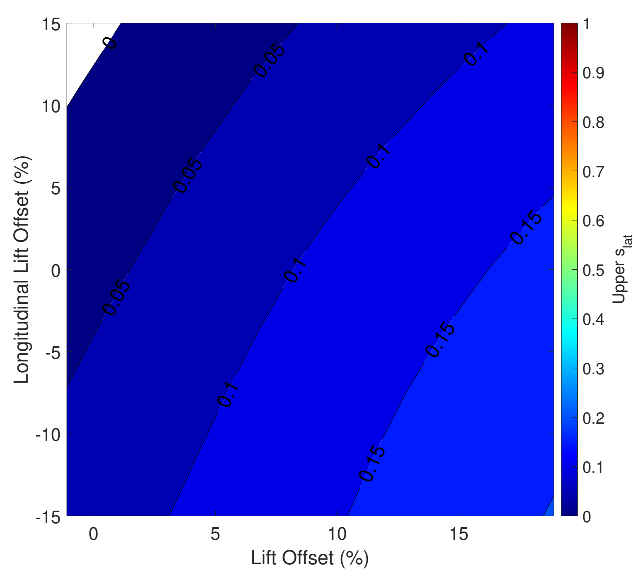

Figure 33. Upper Rotor Lateral Actuator Variation, High Speed LOS Sweep

OVERALL

Considering the collection of results provided, an estimate of the set of achievable trim settings for the different controls can be established. Note that the true ranges according to the model may differ if different controls are swept together (i.e. lateral lift offset and pitch attitude together), but the results presented here demonstrate important relationships in the trim controls in three different flight speeds. Sweeping pitch attitude and elevator setting perturbs the thrust and pitching moment balance on the vehicle, while sweeping the lift offset target perturbs the differential moments in the rotor system. The lateral moment balance could also be considered on the vehicle, however there is no substantial source of lateral moment aside from the rotors, and so deviation from the nominal lateral trim is unlikely to be noteworthy.

The limits in the allowable trim settings can be defined from a number of constraints. For the purposes of this study, geometric limits in the control are considered as well as observed tip clearance limits. Table 6 indicates the approximate servo actuator settings allowable for trim in the different flight regimes.

Table 6. Swashplate Trim Control Ranges

		Upper Rotor			Lower Rotor		
Speed		Aft	Lat	Fwd	Aft	Lat	Fwd
20 kts	Min	0.65	0.5	0.4	0.7	0.5	0.4
	Max	0.9	0.8	0.7	0.95	0.75	0.7
120 kts	Min	0	0.1	0	0	0.15	0
	Max	1	0.35	0.45	1	0.35	0.4
220 kts	Min	0	0	0	0	0	0
	Max	1	0.2	0.6	1	0.25	0.6

First, consider the low speed regime. It was shown that variation in pitch attitude and elevator setting resulted in minimal change in the rotor controls. Therefore, the allowable range of swashplate control settings comes almost entirely from lift offset variation and the corresponding tip clearance limit. This variation is largest in low speed flight because the control couplings that exist in the rotor system are not as significant, so changes in the differential inputs to change the lift offset of the system do not require substantial compensation from the remaining rotor controls. Note that these ranges could change if the tip clearance limit was reduced from 11 inches ($\sim 7\%R$), or if the rotor speed was changed (speeding up the rotor to drive actuator settings lower would be most useful).

At the moderate and high speed case, the distribution of vehicle lift and pitching moment can be changed with the pitch attitude and elevator setting on the tail. As a result, the required collective and longitudinal rotor inputs can change substantially more than they did in the low speed condition. This intuitively would result in an increase in the allowable range for both the forward and aft actuators on the swashplate, but it truly only expands the aft actuator range significantly. This is a result of two effects, the first being that when longitudinal input is increasing (which tends to drive aft actuator up and forward actuator down), the collective pitch is also increasing. This follows directly from the fact that a decrease in tail lift is a decrease in the tail nose-down moment (which happens as the aircraft pitches nose down and the elevator setting is decreased). Because increasing collective increases all of the actuator heights, the change in the forward actuator setting for increasing longitudinal input and increasing collective is largely cancelling. The other effect is the limitation in the control sweep itself, where the elevator setting is not taken into large positive (trailing edge down) settings. This is done to prevent the rotor hub moment from getting large, but if the shaft limits were established the estimated trim range for the forward actuator would expand slightly (again this is modulated by the combined collective-longitudinal influence on the forward actuator).

Variation in differential moments introduces a slight increase in the range of actuator positions compared to the pitch attitude and elevator sweep. Compared to the difference in allowable ranges shown at low speed, there is no substantial benefit to changing the lift offset setting of the rotor. It should be noted, however, that controlling lateral lift offset (either by maintaining a prescribed value or by sweeping it) is the most significant driver of the lateral actuator position in this study. This follows from the fact that the only source of lateral moment aside from the rotor system is the torque from the propeller, which is relatively small.

In each flight speed, the two rotor allowable control settings for each respective actuator are observed to be markedly similar, which is not unexpected especially once the vehicle moves into moderate and high speed flight where the differential collective setting is driven to 0 degrees. In nearly every case considered, the lateral actuator has the smallest allowable range of trim solutions. This is due to the interplay between collective and differential lateral cyclic in moderate and high speed flight. As shown, when differential lateral cyclic is increased ($+\theta_{1s}$) on the rotor in forward flight, the total thrust at the hub increases due to the advancing-retreating side asymmetry in dynamic pressure. Therefore, collective pitch will decrease for increase in differential lateral, and vice versa. Because of this, along with the given swashplate geometry, the lateral actuator generally remains within a small range of positions as the forward and aft actuators move up and down to modulate the collective pitch and differential lateral cyclic in the coaxial rotor system. At low speeds, when the dynamic pressure asymmetry isn't as large, the differential lateral input does not require so large a compensation from collective pitch and the lateral actuator moves more to achieve the differential lateral input. To achieve larger changes in lateral actuator positions, the net rolling moment from the rotor system would need to be varied, which because of the aforementioned lack of redundant effectors in the lateral axis, precludes the trim of the vehicle.

The ranges identified in Table 6 are representative of the aircraft in terms of a departure from a nominal trim case. That is, when certain trim controls are swept, the remaining prescribed controls remain constant at their nominal value (i.e. the elevator setting when lateral lift offset is swept and vice versa). Control ranges would likely change with full simultaneous sweeps of the available trim controls, but this is a highly dimensional problem. The ranges presented here therefore represent somewhat of a conservative estimate of the potential allowable trim settings for the notional X2 model, but still represent a significant improvement over the results indicated for a single main rotor helicopter shown in Refs. 10 and 11.

Conclusions on the allowable ranges of the aerosurfaces are difficult to make definitively without knowing shaft limits on the rotor system. Clearly, there are geometric limits that show up that follow from limited cyclic range at low collective settings, but true limitations in the elevator setting (especially for positive deflections) would require knowledge of the shaft moment limitations, as well as an aerodynamic model to capture the interference between the rotor wake and tail structure. Intuitively, a hard-over failure of a rudder or elevator surface would be quite dangerous at the high speed end of the flight envelope, but as the airspeed decreases the allowable range of surface deflection for these controls expands to the full travel.

CONCLUSIONS

The present study describes the development and implementation of an elastic blade coaxial-pusher helicopter trim model based on the X2 Technology™demonstrator. This model uses published rotor data and geometry, a pressure potential superposition inflow model (PPSIM) to predict the mutual interference between the coaxial rotors, as well as an elastic blade model to calculate the elastic deflection of the rotor blade out of plane. This trim model is validated against experimental data both from coaxial rotor systems and flight test data from the Sikorsky X2 program.

The trim model is then used to explore trim control variation in different flight regimes (enabled by redundant control effectors) including low speed (20 kts), moderate speed (120 kts), and high speed (220 kts). Parametric sweeps of vehicle pitch attitude and elevator setting were performed to examine redistribution of the vehicle lift and pitching moment balance, as well as sweeps in the longitudinal and lateral lift offset to examine the effect of differential moments in the rotor system as it applies to trimmable input ranges.

At low speed, the effect of pitch attitude and elevator setting is small relative to the other speeds because the rotor is the dominant source of force and moment. Variation in the differential moments in the rotor system allows for an expansion of the trim control settings (considering the generalized swashplate actuator positions), allowing for approximately 30% of the actuator throw to be trimmed within the 11 inch tip clearance limit. This range would expand with a relaxed tip clearance limit should the situation permit it.

At moderate and high speed, the effect of pitch attitude and elevator setting becomes significant due to the increased dynamic pressure on the fuselage and tail. This allows for a redistribution of the forces and moments required for aircraft trim, and so the allowable set of trim controls expands relative to low speed, where the aft actuator on each swashplate can vary over the entirety of its throw, the forward actuator can trim through 40-60% of its throw, and the lateral actuator can trim over 20-25% of its throw. The reduction in the forward actuator range is due to the interplay of collective and longitudinal input required for trim, where the small lateral actuator range is due to the inability of the aircraft to redistribute roll moment balance away from the rotor, as well as the coupling between differential lateral cyclic and collective pitch in forward flight.

The control ranges demonstrated exceed that of a traditional single main rotor helicopter and an advanced lift/thrust compounded helicopter, especially in low speed, because of the effectiveness of the dual rotor system even in hover. While a failure in the single main rotor swashplate can only be accounted for by additional aircraft effectors (which typically require significant dynamic pressure for control authority), a failure in the swashplate of one of the coaxial helicopter rotors can in some cases be mitigated by an adjustment in the opposing rotor. This feat enables the coaxial helicopter to tolerate larger ranges of actuator failure relative to the single main over a wider range of airspeeds.

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