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PITCH CONTROL OPTIMISATION OF TILTROTOR AIRCRAFT

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Abstract

An investigation into the effects of rotary-wing and fixed-wing control gearings for tiltrotor aircraft was undertaken. The work investigated the effects of different cyclic and elevator gearings (both prescribed and optimised) on the longitudinal trim behaviour through the conversion regime of flight. The numerical simulations were performed for the XV-15 tiltrotor aircraft using an in-house aeromechanics code. This was coupled to a genetic algorithm to perform the optimisation studies. The findings show the control gearings must be selected carefully to maximise the conversion space and that the gearings can be optimised to meet different objective function requirements of the trim parameters. Fixed-wing control was found to be complimentary at lower airspeeds to help reduce excessive stick and cyclic inputs.

1. INTRODUCTION

Tiltrotor aircraft amalgamate the advantages of both rotary-wing and fixed-wing aircraft into a single flight vehicle. The advanced configuration exploits the hovering and V/STOL capabilities of rotorcraft along with improved speed, range and altitude capabilities of turbo-prop fixed-wings. The configuration consists of two counter-rotating wing-tip mounted rotors that are tiltable through at least 90°. In helicopter mode (rotor shafts vertical), the rotors provide all the lift, propulsive and control forces due to the low freestream dynamic pressure. As the rotors are tilted forwards and the aircraft gains forward speed, the vehicle lift is offloaded to the wings and the rotors provide mostly a propulsive force. In aeroplane mode (rotor shafts horizontal), the wing provides all the aircraft lift with the propulsive force generated by the rotors and the control forces by the empennage.

The conversion corridor of the aircraft represents the flight envelope of the aircraft in terms of the airspeed and rotor tilt angle. Through the conversion corridor, the aircraft remains controllable through a combination of rotary-wing and fixed-wing controls. Fixed-wing controls consist of standard control surface deflections and rotary-wing controls consist of standard collective and cyclic controls, along with differential control inputs to generate yawing/rolling moments. The existence of two sets of control methods presents a design challenge to ensure adequate control is available throughout the flight space. Fundamentally, the control system is not unique and the required control inputs depend on the control system architecture. The rotary-wing and fixed-wing control inputs are geared to the pilot controls (stick, pedals and collective/power lever) throughout the operating space to augment the level of control from each source. For a specified control input amplitude, the control gearings represent the fraction of the control amplitude available at full pilot input, e.g. an elevator with a

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control amplitude of 20° geared at 0.50 will have a deflection of $\pm 10^{\circ}$ at full fore/aft stick position.

The current work investigates the longitudinal flight of tiltrotor aircraft operating through the conversion corridor. Many mathematical models of tiltrotor aircraft typically reduce the longitudinal rotor control inputs with respect to the rotor tilt angle so there is no coupling between the stick and longitudinal cyclic control in aeroplane mode[1-3]. The rotors are, however, still free to flap at all operating points. The exact phasing of the control gearings is somewhat arbitrary and needs to be designed to provide the required control inputs when commanded by the pilot. Several sources state the rotary-wing and fixed-wing control gearings are blended together through the conversion corridor to provide good control, however, do not detail the exact control functions used[4,5]. Typically, linear functions, sines or cosines are used to blend the two control methods[6]. The control gearings, coupled with any stability and control augmentation, should be designed to improve the aircraft handling qualities and where possible, reduce pilot work. This is particularly true during conversion when the pilot must fly through a fairly narrow range of airspeeds at given rotor tilt angles.

The aircraft modelled in this work was the Bell XV-15 tiltrotor research aircraft owing to the large volume of publicly available data. The purpose of this investigation was to understand the effects of the different control gearings (longitudinal cyclic and elevator for the XV-15) on the steady-state trim behaviour through conversion flight. The trim parameters investigated were the fuselage pitch θ_F, pilot fore/aft stick position δ, longitudinal rotor flapping β_{1c} and required rotor power P. The fore/aft pilot stick position was used as the parametric parameter to determine the longitudinal cyclic and elevator inputs related to the control gearing and stick position. Previous work has shown the trim behaviour is significantly affected by component interactions and there is an implicit coupling between the pitch, stick and flapping[7]. The longitudinal trim solution of the aircraft is also dependent on the flap/flaperon setting and the tailplane incidence angle. To investigate the effects of the control gearings, numerical simulations were performed firstly using simple prescribed gearing functions. This was followed by multi-objective optimisation of the control gearings to ascertain if further improvements in the trim parameters/behaviour could be achieved.

2. NUMERICAL MODELS

2.1. Tiltrotor Model

The numerical simulations of the aircraft were performed using TARA (Tiltrotor AeRomechanics Analysis), an in-house aeromechanics code developed at the University of Manchester. The aeromechanics code was written in MATLAB using an object-orientated approach that easily facilitates the creation of generic tiltrotor aircraft. The code couples a main flight mechanics module with several aerodynamic modules that are called depending on the component class being analysed. TARA also facilitates interactions between different components. TARA attempts to trim the aircraft at a specified operating point using a damped Newton-Raphson scheme that iterates the trim quantities and enforces periodicity in the rotor state-space model. A summary of the aeromechanics model within TARA is shown in Figure 1. Changes in the aircraft cg position and inertia properties with respect to rotor tilt are also handled within TARA. The XV-15 model within TARA was configured largely from the validated Generic TiltRotor Simulation (GTRS) model[2,8]. Trim predictions by TARA can be found in previous works by the authors[7,9] and show good agreement against the available trim data[8].

The flight conditions simulated in this work constitute the conversion corridor. This comprises helicopter, conversion and aeroplane mode flight. No reference conditions could be found in literature that defines the XV-15 conversion corridor and, therefore, the operating points simulated in this work were taken from Ferguson[8]. During transition, the rotor incidence angle, blade

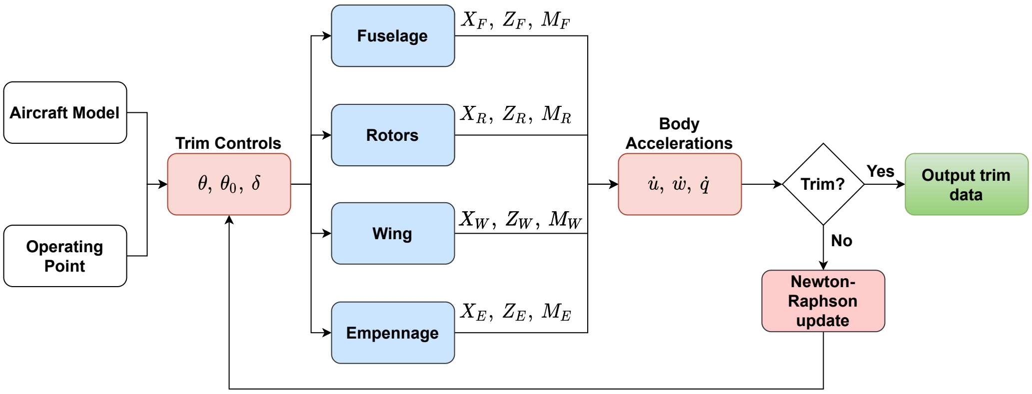


Figure 1: Overview of the trim routine implemented within TARA.

loading and dynamic pressure change significantly and the influence of the control gearings is most pronounced. The operating points, summarised in Table 1, are assumed to represent generic XV-15 flight through the conversion corridor before the final reconfiguration into high-speed aeroplane mode is made (retracted flap/flaperons and reduced rotor speed).

Table 1: Simulated flight conditions.

KTAS [kn]	0 - 180
Rotor tilt, τ [°]	0 (heli.) - 90 (aero.)
Flight path angle [°]	0
Mass [kg]	5900
CG position	Aft limit (helicopter mode)
Flap/flaperon settings	$40.0^\circ/20.0^\circ$ ($\tau \leq 15^\circ$) $20.0^\circ/12.5^\circ$ ($\tau > 15^\circ$)
Tailplane setting [°]	0
Rotor speed [rpm]	589
Altitude	sea-level

Within the control gearing investigation, the gearings were varied and TARA then attempted to trim the aircraft to the specified operating point. If a trim solution was found, the result returned by TARA was checked to ensure the solution was valid and did not break any performance constraints. These constraints were based on literature data for the XV-15 for the rotor flapping and power[10]:

1. Absolute rotor flapping does not exceed 12°: $|\beta| \leq 12^\circ$
2. Required rotor power does not exceed the installed power: $P \leq 930\,\text{kW}$ (for a single rotor)

A pitch constraint was also implemented, however, no reference value could be found in literature. Therefore, the pitch attitude constraint was based on a reference value similar to that of a tiltwing aircraft[11]:

3. Absolute fuselage pitch attitude does not exceed 15°: $|\theta_F| \leq 15^\circ$

Any solution found that was outside the constraints of the aircraft was discarded or penalised within the optimisation routine to ensure the control gearings were not taken forwards.

2.2. Control Model

The pitch control of tiltrotor aircraft is an under-determined degree of freedom with both rotary-wing and fixed-wing controls available, albeit with different authorities depending on the flight condition. The rotary-wing pitch control is implemented as longitudinal cyclic that 'flaps' the rotor thrust vector and the fixed-wing pitch control is implemented as, for this study (depending on empennage configuration), an elevator deflection. In order to close the pitch control system, the rotary-wing and fixed-wing controls are related to a single parametric variable: the fore/aft pilot stick position δ. The longitudinal control system implemented in the GTRS model of the XV-15 is given by[2]:

$$(1)\quad \theta_s = -10^\circ \cos\tau\,\delta - 1.5^\circ(1-\cos\tau)$$

$$(2)\quad \eta = \; 20^\circ \quad \delta$$

where θ_s is the longitudinal cyclic input, η is the elevator deflection, τ is the tilt angle of the rotor shafts measured from vertical and δ is the fore/aft pilot stick position. As seen in Equations 1 and 2, the cyclic pitch input with respect to the stick position is washed-out with rotor tilt angle leaving a small rigging angle in aeroplane mode.

In order to perform the optimisation study, the control architecture was recast generically as

$$(3)\quad \theta_s = -10^\circ \frac{\partial\theta_s}{\partial\delta}\,\delta$$

$$(4)\quad \eta = \; 20^\circ \frac{\partial\eta}{\partial\delta}\,\delta$$

where the control input amplitudes (10° and 20°) were retained and $\partial\theta_s/\partial\delta$ and $\partial\eta/\partial\delta$ are the control gearings of the longitudinal cyclic and elevator deflection with respect to the fore/aft pilot stick position. The gearings are to be optimised at each discrete airspeed V_∞ and rotor tilt angle τ, $\partial\theta_s/\partial\delta = f(V_\infty,\tau)$ and $\partial\eta/\partial\delta = g(V_\infty,\tau)$, where f and g are arbitrary functions.

2.3. Genetic Algorithm

The Genetic Algorithm (GA) is a subset of the evolutionary algorithm group of optimisation strategies[12]. The GA is built around processes borrowed from natural selection in order to successively improve a populations performance. The GA is a stochastic optimisation method and does not rely on computing the gradient of the objective function. As a result, the GA is a robust optimisation process that is capable of handling complex objective functions. In the present work the MATLAB Genetic Algorithm toolbox[13,14] has been used to carry out the optimisation of the control gearings.

Optimisations were carried out to find the optimal combinations of cyclic and elevator gearings in order to minimise the absolute value of a number of tiltrotor trim variables across the conversion corridor. In order to handle multiple objectives, the weighted sum approach[15] was implemented within the optimiser. The weighted sum approach was chosen for its simplicity in implementing within the current preliminary framework. The weight assigned to each objective is used to reflect their relative importance within the optimisation. In the present case, all objectives were equally weighted. A number of additional weighting methods (random and product) were also investigated but offered no advantages over the present method.

When handling multiple objectives with the weighted sum approach, it is important to ensure that objectives are suitably normalized in order to avoid introducing artificial weighting. Therefore, to ensure fair weighting, a procedure was developed to normalise each objective at each operating point. Prior to each optimisation run, the control gearing design space was coarsely swept to find the maximum value of each objective independently. This maximum value was then used to normalise each objective. This normalisation ensured objectives could be fairly summed with objective values of similar magnitudes and representing relative performance changes. A max/min normalisation was also studied but offered no significant change in the resulting optimal gearings.

2.4. Control Gearing Investigation

The control gearings were investigated through both prescribed functions and optimisation studies. The prescribed gearing functions were, in the first instance, taken to be simple trigonometric functions with respect to the rotor tilt angle. However, due to the diverse aerodynamic environments seen by the rotors, wing and empennage components, more complex functions could be formulated that depend on other additional parameters such as rotor tilt, airspeed and angle-of-attack. The prescribed control gearings investigated in this preliminary study are summarised in Table 2. The first prescribed gearings utilised the GTRS gearings whereas the second prescribed gearings washed the elevator control in as the longitudinal cyclic was washed out with respect to the rotor tilt. The control gearings were then optimised in a multi-objective framework in order to meet the two following objectives:

1. Minimise fuselage pitch attitude and pilot stick position
2. Minimise fuselage pitch attitude, pilot stick position and rotor flapping

The objective functions were formulated in order to minimise the pilot workload through transitioning flight and improve the available control margins for manoeuvring flight. In the first instance, only the fuselage pitch and pilot stick position were optimised. In the second instance, the rotor flapping was included to minimise flapping amplitude and to compare differences in the optimised control gearings. The optimisations were run at airspeed intervals of 5kn inside the airspeed and rotor tilt angle domains summarised in Table 3.

Table 2: Prescribed control gearings.

Gearing #	$\partial\theta_s/\partial\delta$	$\partial\eta/\partial\delta$
1	$\cos\tau$	1
2	$\cos\tau$	$1-\cos\tau$

Table 3: Simulated flight conditions.

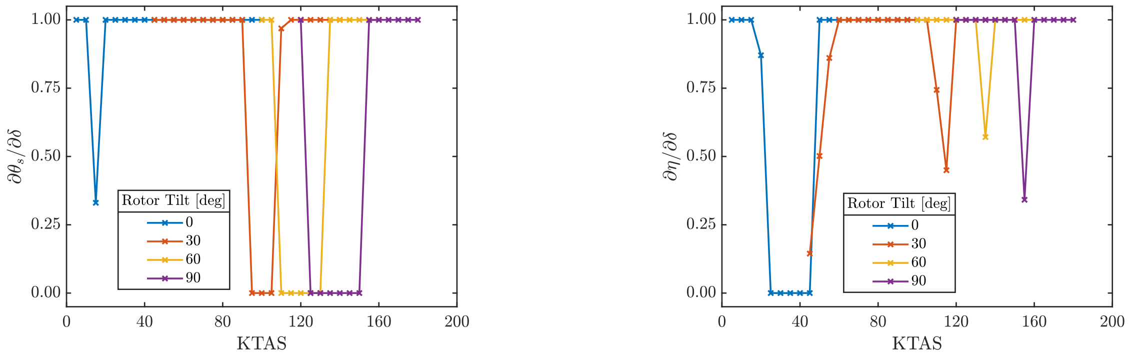
Rotor Tilt [deg]	Min. Airspeed [kn]	Max. Airspeed [kn]
0	0	100
30	0	140
60	100	160
90	120	180

3. RESULTS & DISCUSSION

The raw data for the control gearing optimisations of pitch and stick (OPS) and pitch, stick and flapping (OPSF) are shown in Figure 2. The raw data for both sets of optimisation data shows fairly erratic behaviour with the control gearings quickly flipping between values of 0 and 1 in many instances. This implies the gearings quickly switch from being either fully engaged or fully disengaged between very similar operating points. This was likely due to the uniform-weighting approach utilised within the optimisation routine, whereby the variation in the control gearings had only a small influence on the minimum value of the objective function. Further work will seek to implement a modified optimisation approach that potentially better ranks the optimisation variables with the hope of reducing variability.

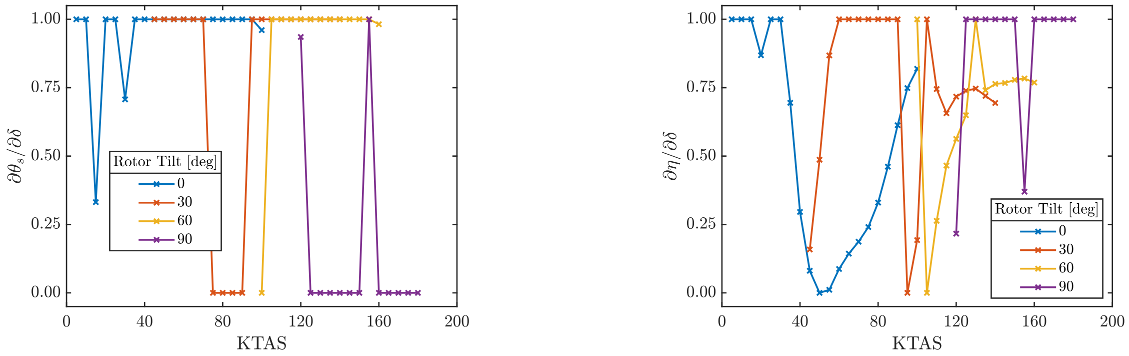
From a practical perspective, the control gearings are required to be smooth functions and, therefore, the raw data needed to be smoothed. For the OPS control gearings, the smoothed gearings were taken to simply be $\partial\theta_s/\partial\delta = 1$ and $\partial\eta/\partial\delta = 1$ at all operating points. For the OPSF control gearings, the longitudinal cyclic gearing was taken to be fully engaged for all rotor tilt angles except for aeroplane mode where it was fully disengaged. The elevator gearings at all rotor tilt angles were smoothed using a fourth-order polynomial least-squares fit. Figure 3 shows the fitted control gearing data. The influence of the flapping objective in the optimisation investigation is shown to have a significant effect on the elevator gearings through transitioning flight. Conversely, the optimised longitudinal cyclic gearing in aeroplane mode for the OPS and OPSF shows the cyclic to be an effective method to reduce flapping in this flight mode. The large variability in the optimised control gearings potentially suggests that the gearings could be better optimised based on only rotor tilt alone (and left constant over all airspeeds) or that the specific control gearings could be implemented over fixed airspeed ranges (e.g. 20kn intervals) as opposed to point-by-point gearings.

The required power was found to be minimally affected by all the control gearings, both prescribed and optimised, at all operating points. The dominant parameter that effects the required power, particularly at higher airspeeds, is the flap/flaperon setting. Varying this parameter has a significant impact on both the wing and overall



(a) Longitudinal cyclic gearing for the OPS case

(b) Elevator gearing for the OPS case



(c) Longitudinal cyclic gearing for the OPSF case

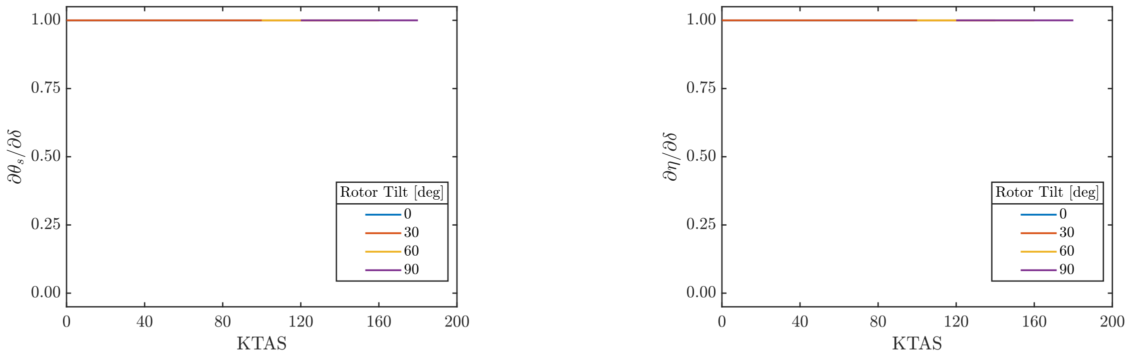
(d) Elevator gearing for the OPSF case

Figure 2: Raw optimisation data for the OPS and OPSF cases.

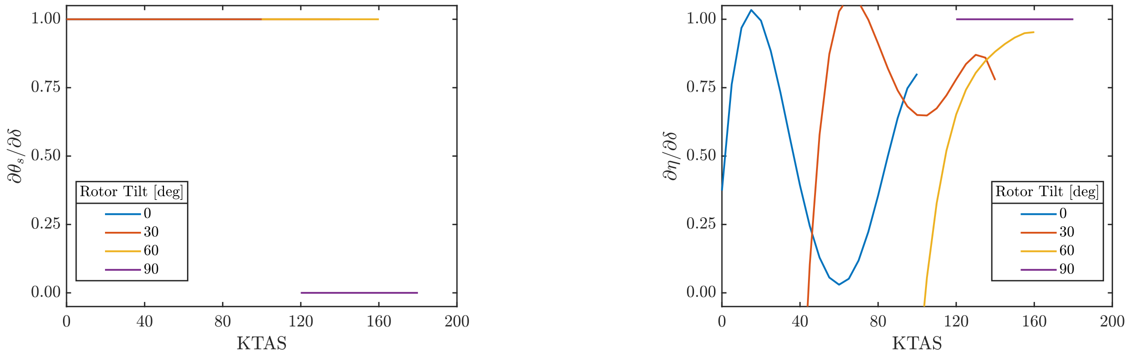
aircraft drag which is compensated by higher rotor thrusts and power. As a result, power considerations were omitted herein. Further studies are to be performed to devise an optimised flap/flaperon scheduling that minimise required power through the transition phase.

Trim parameter plots at different rotor tilt angles and for different control gearings are presented in Figures 4 to 7. The figures show that optimising the control gearings on a point-by-point basis can have a significant impact on the trim variables relative to the prescribed gearing functions. The raw data further identified the gearings needed to be smoothed in order to ensure a smooth transition of the trim parameters on a point-by-point basis. Moreover, the trim solutions were found to be influenced by the control gearings throughout transition, though the degree of influence was dependent on the trim parameter. For instance, the fuselage pitch was found to be most influenced by the control gearings with the rotors vertical. At these lower airspeeds, this dependency was caused by the implicit coupling between the fuselage pitch and stick, where the latter controls the orientation of the rotor thrust vector through cyclic and the resulting flapping. At these operating points, the rotor was required to provide most the aircraft lift, the propulsive force and also the control moment. Both the prescribed and optimised control gearings had minimal influence on the fuselage pitch at the other rotor tilt angles.

The fitted control gearings showed no significant detrimental effect on the trim variables and in most cases ensured their smooth transition with airspeed. However, in some instances, the smoothed optimised gearings were found to present some undulations in the trim parameters, particularly the stick position, that may be adverse from a pilot's perspective. There is, therefore, a trade-off between the raw optimised control gearings and how the data is fitted, particularly due

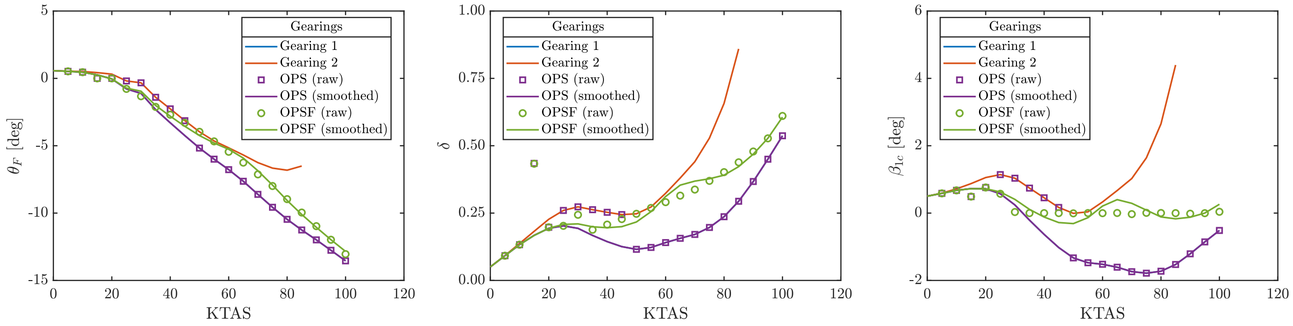


(a) Longitudinal cyclic gearing for the OPS case **(b)** Elevator gearing for the OPS case



(c) Longitudinal cyclic gearing for the OPSF case **(d)** Elevator gearing for the OPSF case

Figure 3: Smoothed optimisation data for the OPS and OPSF cases.

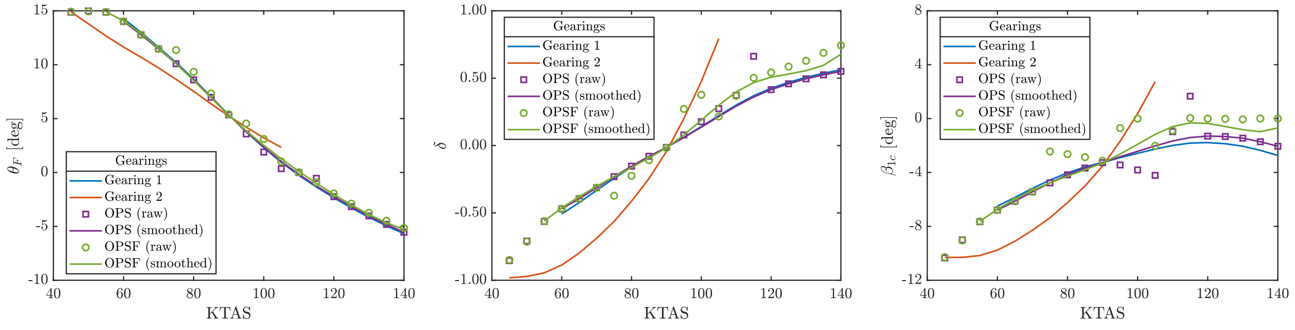


(a) Fuselage pitch **(b)** Fore/aft stick **(c)** Longitudinal flapping

Figure 4: Trim parameters at 0° rotor tilt angle.

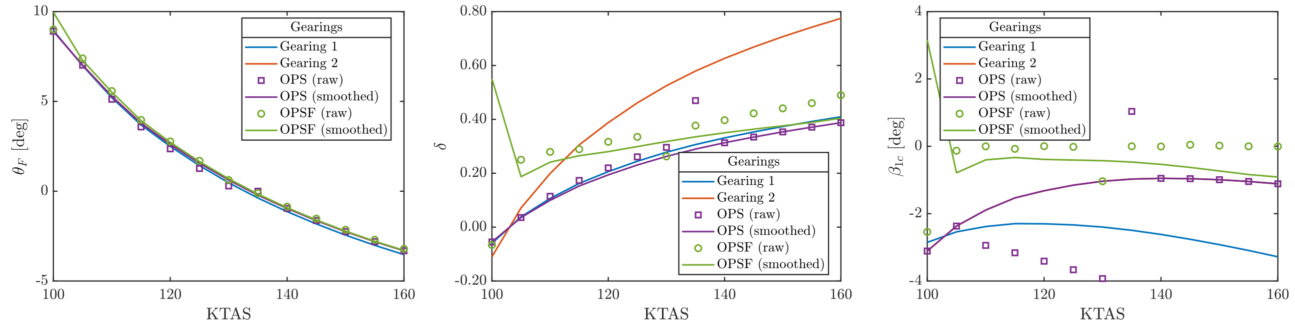
to the large gradients of the gearings with respect to airspeed. Additionally, the fourth-order polynomial fit of the elevator gearing in Figure 3d is seen to extend beyond the gearing limits of 0 and 1. When the trim simulations were rerun using the fitted gearings at 30° rotor tilt, an invalid trim flag was returned by TARA since the limits of the lookup tables were exceeded. As seen in Figure 5, this occurred near the lower speed limit were the pitch, stick and flapping were near the constraint limits. This point is further highlighted for the OPSF case at 100kn for a rotor tilt of 60° where the optimised control gearings shows an erratic trim result compared with the raw data. This also shows there can be significant sensitivity in the trim parameters to the control gearings.

Inspection of the trim parameters for each non-zero shaft angle, Figures 5 to 7, shows a



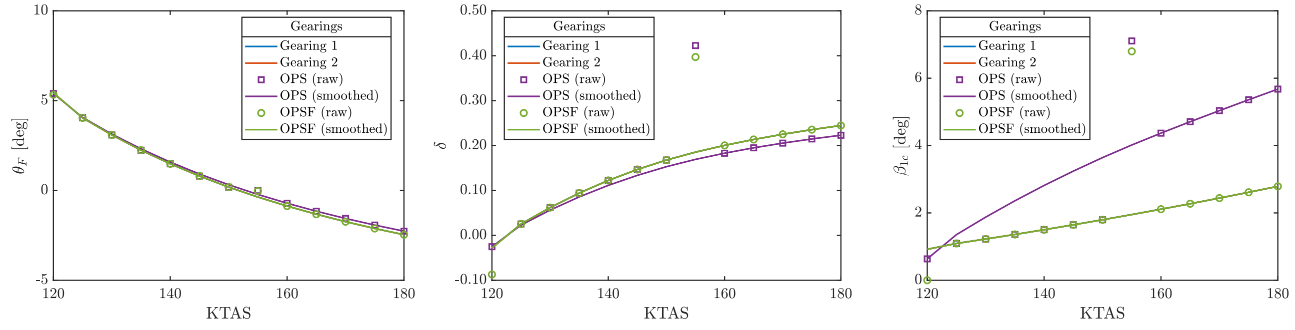
(a) Fuselage pitch **(b)** Fore/aft stick **(c)** Longitudinal flapping

Figure 5: Trim parameters at 30° rotor tilt angle.



(a) Fuselage pitch **(b)** Fore/aft stick **(c)** Longitudinal flapping

Figure 6: Trim parameters at 60° rotor tilt angle.



(a) Fuselage pitch **(b)** Fore/aft stick **(c)** Longitudinal flapping

Figure 7: Trim parameters at 90° rotor tilt angle.

common outlier at $\sim$ 85% of the maximum speed for each shaft angle. This point corresponds to where the pitch angle goes from positive to negative and where the pitch objective transforms from a minimisation to a maximisation problem. This presents a particular challenge to the optimisation and is a result of how the problem has been formulated and the use of the weighted sum approach. To alleviate the issues of such outliers, polynomial curve fits through the raw data were used. As previously described, there are a number of issues associated with smoothing the data and, therefore, this will be investigated further in future work.

Comparing the trim variables between the two optimisation cases demonstrates the flapping could be substantially reduced. This shows the gearings could be used to potentially reduce excessive flapping at extreme operating points. When the flapping was not included in the optimisation study, the flapping was found to quickly change between similar operating points as seen in Figures 5c to 7c. These points corresponded to where the pitch changed sign as discussed previously.

Figures 4 and 5 show a reduced airspeed range for the second prescribed gearing (gearing 2) and demonstrate that the control gearings must be selected carefully in order to maximise the flight envelope. For this prescribed gearing, the elevator control was washed-in with respect to the rotor tilt and, therefore, there was minimal elevator deflection at rotor tilts of 0° and 30°. In these cases, the pitching moment generated by the tailplane can be significant and without elevator implementation, the resulting moment must be trimmed out through a combination of pitch and rotor flapping. As a result, large stick displacements were found to be necessary that were beyond the limits of the control system. Consequently, the trim solutions were invalid with the airspeed limits found to be stick-limited in many instances. Therefore, allowing the elevator control at higher airspeeds in helicopter mode was therefore found to be beneficial to alleviate excessive forward stick positions and maximise the permittable airspeed range. The first prescribed gearing, as implemented in the GTRS model, was found to give satisfactory trim behaviour throughout the conversion corridor. However, the OPSF gearings were found to give smaller flapping angles overall.

4. CONCLUSIONS

This study has presented an investigation into the rotary-wing and fixed-wing control gearings for tiltrotor aircraft. The conversion domain was simulated using two prescribed control gearings followed by an optimisation of the gearings to meet two multi-objective functions. The control gearings were found to influence the trim parameters and successfully showed the gearings could be optimised to meet different objective criteria. The raw optimisation data of the gearings was found to be fairly scattered and required smoothing to be implemented practically. Fitting the data was difficult due to the scattering and suggested a different optimisation approach may be needed in the future.

The predicted power was found to be minimally affected by the control gearings at all operating points and driven largely by the flap/flaperon deflections instead. When the minimisation of the rotor flapping was included in the optimisation, a significant difference in the elevator gearing was found compared to the case where the flapping was omitted in the objective function. It was found the control gearings must be selected carefully in order to maximise the available airspeeds at each rotor tilt. Washing-in the elevator with respect to the rotor tilt angle was found to be unfeasible due to the large stick and control input requirements. Fixed-wing control should be retained at all operating points to help alleviate the tailplane moment and reduce cyclic input requirements. Future work will seek to refine the control gearings further by firstly improving the optimisation framework and then look to optimise the gearings for individual rotor tilts and/or over set airspeed intervals.

5. ACKNOWLEDGEMENTS

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