SIMULATION OF TILTROTOR MANEUVERS USING LINEAR PARAMETER VARYING MODELS

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Abstract

This work introduces a numerical approach to simulate a complex maneuver of a rotorcraft without calling into action complex nonlinear aeromechanic models. By using a set of a Linear Parameter Variable models of a rotorcraft, i.e. basically a set of linear models to be interpolated, it si possible to represent with a sufficient accuracy a complex maneuver that cannot be modeled using a single linear model. This approach is used to perform the evaluation of the best path to be followed during a conversion maneuver of a tiltrotor.

1 INTRODUCTION

This work aims at developing a numerical model able to simulate a complex maneuver of a rotorcraft without calling into action complex nonlinear aeromechanic models. To model in an appropriate way the tiltrotor dynamics in any flight condition included within the conversion corridor a complex nonlinear dynamic model should be considered, such has those presented in[1]. However, such a model would be difficult to develop and validate, but also very complex to be employed for the synthesis of the controller that should guide the conversion. For these reasons a different approach based on the Linear Parameter-Varying (LPV) technique has been chosen[2]. Such a model can be proven very useful when it is necessary to make the synthesis of a flight control system. At the same time, this approach may lead to aeroelastically accurate models to be used as simulator engine by a flight simulator, as done in Ref.[3], that may run with a limited computational burden.

A classical modeling approach for control design is based o the usage of linearized state space perturbation models, representing the dynamic response of the aircraft for a set of reference flight condition and configuration. This way of doing has a long tradition in the control engineering community, and in particular in the one dedicated to the development of flight control, and has been typically called *gain scheduling*[4;5]. The approach is simple and, following[5] can be summarized in the following steps: choose a a set of scheduling variables that parametrize the space of possible configuration and trim conditions; define a family of linearized models that cover the design space; design a parametric controller that is able to cope with each operative point and that ensures an acceptable behavior during the (slow) transient between the operative conditions.

In the last decades the Liner Parameter Variable (LPV) control synthesis has been developed starting from the early, often heuristic, gain scheduling approaches, leading to a more reliable and systematized field with local stability and performance assurance results[4]. As correctly noted by[4], the application of LPV control synthesis requires to use LPV models instead of nonlinear models. However, it is necessary to identify clearly the soundness and range of employment of LPV models to represent a full flight envelope simulation model. A good analysis of LPV models used for aircraft application can be found in[4]. Application of a similar modeling approach to the specific rotorcraft field can be found in[6;7], where the technique is denominated *model stitching*, or in[8] where a flight simulator model is developed. Lawrence et al.[9] exploited this approach to build a tiltrotor simulation model for the investigation of the handling qualities at low speed.

The LPV approach is here used to model the flight dynamics of a tiltrotor. Tiltrotors combine the capability of helicopters to hover, take off and land vertically, with the high cruise speed of airplanes. This is obtained by means of two large proprotors mounted on nacelles that can tilt modifying the aircraft layout. To allow the aircraft to gain speed, the rotors are progressively tilted forward, with the plane of rotation eventually becoming vertical[10].

This work aims at developing a numerical methodology to simulate several different conversion path within the conversion corridor that could be followed during a conversion from helicopter mode to airplane mode and vice-versa. The idea is to start from a LPV model of the XV-15 tiltrotor to better investigate the conversion maneuver, and in particular to understand what are the optimal trajectories that should be followed within the conversion corridor to exploit the capabilities of an automatic nacelle control system. The paper proceeds as follows: the first section introduces the LPV approach and how it can be used for simulation of nonlinear aircraft. Then, the conversion maneuver is presented together with the the different models that are required: the tiltrotor LPV model, and the model of a virtual pilot that drives the aircraft through the maneuver. The presentation of the results obtained and the lessons learned close the paper.

2 TILTROTOR CONVERSION

The maneuver that characterizes a tiltrotor from other rotorcraft is the conversion, i.e the tilting of rotor axes from the vertical to the horizontal position and vice versa. A tiltrotor can safely execute this maneuver flying within a particular region of the airspeed–nacelles angle domain called *conversion corridor* because of it's particular shape. Flight outside the conversion corridor may lead to stability or handling quality problems, or to excessive torque or fatigue loads that may damage the structure[10].

The conversion is accomplished through a switch located on the power level, or collective lever, see[11]. Whenever the pilots activate the switch, the nacelle starts rotating. In the interval between 90 and 75 deg the rotation of the nacelle is at a constant rate and can be stopped at any intermediate position. At 75 deg the first *detent* is reached and the rotation is stopped. To decrease the nacelle angle to values lower that 75 deg the pilot acts again on the switch starting a rotation of the nacelle at a constant rate to the second *detent* at 50 deg and then to 0 deg. A conversion can be complete in 12 seconds[12]. During the entire conversion phase the rotor rpm are kept at 100% as for the helicopter configuration. After reaching the airplane configuration the rpm are reduced to the value optimized for forward flight. Rotor controls are phased out as the conversion process progresses to the airplane mode at least for the control around the pitch and roll axes that are obtained through classical movable surfaces.

Typically the maneuver start with an initial tilt of 20 deg of the nacelle and an acceleration to a velocity above the minimum velocity allowed within the conversion corridor, followed by a continuous conversion with a significant forward acceleration[11]. The reconversion from airplane mode is done in a similar way going through a deceleration. To increase the pilot awareness a conversion angle indicator is included in the instrument panel[11]. The maneuver is of course quite peculiar, but in general is considered ”a low-workload, straightforward process”[11], at least on the XV-15. However, the pilot has to compensate for pitching moments and this has to be add to the change of mental model required to the the pilot that must switch the handling approach between the rotating and fixed-wing aircraft control.

The current conversion maneuver is fully driven by the pilot. This may introduce several shortfalls, especially if considered the potential wider employment of this type of aircraft for civil use, if the current design under development, like the Leonardo AW609, will be successful. In fact, it may be expected that during the departures and final phases of approach to terminal areas the aircraft will have to comply with operational guidelines and regulations to ensure the safety of flight while operating in areas with heavy air traffic. In this situation a reduction of the pilot workload will be mandatory. Additionally, with the current ”manual” conversion approach it will not be possible to introduce a robust envelope protection system that will mitigate the hazard associated with exceedance during flight of the conversion corridor boundaries.

An automatic nacelle control system could be effective in improving and simplifying the aircraft handling during the conversion maneuver, reducing the pilot workload and increasing the flight safety. The development of such a system is envisaged in the Patents filed by[13;14].

By developing such a system it will be possible to perform a conversion maneuver that is somehow optimal with respect to parameters that are not only related to the workload, but also to other aspects, such as alleviation of structural static and fatigue loads, minimization of the hazard in case of failure during the maneuver and so on.

In order to design such a control system it is necessary to have a detailed aeromechanic model capable to perform a complete simulation of the conversion maneuver. Given the extension of the variation of configurations the employment of a nonlinear model is mandatory. Detailed models able to simulate such kind of maneuver are often multibody models such as those developed in[15;1]. However, the extraction of the information necessary to design such control system may be cumbersome.

3 LINEAR PARAMETER VARIABLE MODELING

A LPV system is a defined as linear state-space system where all state matrix depend on a scheduling

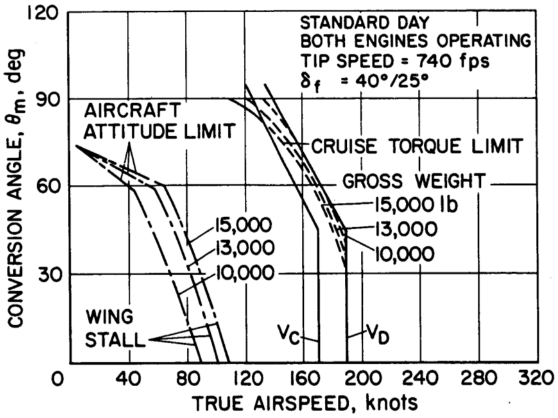


Figure 1: XV-15 conversion corridor from[10].

parameter vector $\boldsymbol{\rho}$

$$\begin{Bmatrix} \dot{\mathbf{x}} \\ \mathbf{y} \end{Bmatrix} = \begin{bmatrix} \mathbf{A}(\boldsymbol{\rho}(t)) & \mathbf{B}(\boldsymbol{\rho}(t)) \\ \mathbf{C}(\boldsymbol{\rho}(t)) & \mathbf{D}(\boldsymbol{\rho}(t)) \end{bmatrix} \begin{Bmatrix} \mathbf{x} \\ \mathbf{u} \end{Bmatrix}. \tag{1}$$

The system is called *quasi*-LPV (qLPV) if the scheduling vector is composed by a subset of the states, called scheduling states $\mathbf{x}_s$ plus a set of exogenous variables $\boldsymbol{\omega}$, i.e. $\boldsymbol{\rho} = [\mathbf{x}_s, \boldsymbol{\omega}]^T$.

Consider a nonlinear state space aircraft model:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{F}(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} &= \mathbf{G}(\mathbf{x}, \mathbf{u}) \end{aligned} \tag{2}$$

for which a set of trim condition $(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})$ is known. Using a first-order Taylor-series expansion with respect to a trim point, the following linearized system is obtained

$$\begin{aligned} \delta\dot{\mathbf{x}} &= \nabla_{\mathbf{x}}\mathbf{F}(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})\delta\mathbf{x} + \nabla_{\mathbf{u}}\mathbf{F}(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})\delta\mathbf{u} \\ \delta\mathbf{y} &= \nabla_{\mathbf{x}}\mathbf{G}(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})\delta\mathbf{x} + \nabla_{\mathbf{u}}\mathbf{G}(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})\delta\mathbf{u} \end{aligned} \tag{3}$$

with $\delta\mathbf{u} = \mathbf{u} - \tilde{\mathbf{u}}$, $\delta\mathbf{y} = \mathbf{y} - \tilde{\mathbf{y}}$, $\delta\mathbf{x} = \mathbf{x} - \tilde{\mathbf{x}}$. The state-space matrices in eq. (3) depend on trim values and all trim values $(\tilde{\mathbf{x}}, \tilde{\mathbf{u}})$ are function of the scheduling values, so the LPV system derived in this way it is always a qLPV. Being eq. (3) a first-order approximation, it could lead to divergent behavior with respect to the nonlinear model for large control inputs. A comparison of the open-loop time response obtained by the qLPV model and the high-fidelity nonlinear model is presented in[4].

4 A MODEL TO SIMULATE CONVERSION MANEUVER

Every tiltrotor designed has its particular conversion corridor but they basically share the same form. Figure 1 is a detailed representation of the XV-15 conversion corridor. The limits are related to aerodynamic stall, excessive aircraft attitude or load limits.

In order to simulate a conversion three elements are necessary:

- an LPV model of the tiltrotor;
- a virtual pilot model able to stabilize the aircraft and ”fly” it through the application of the controls required to perform the conversion maneuver;
- a tracking reference signal which is the desired flight path of the aircraft during the conversion and that is the facto the set of parameters used in the optimization process.

In general, given the large variability in the dynamics of the aircraft when large configuration changes are considered, also the virtual pilot model needs to be adapted. Consequently, also the pilot will be modeled as an LPV system, obtained interpolating the pilot models designed about each linearized aircraft model.

To simulate the conversion maneuver it is necessary to define the appropriate reference input to be given to the tiltrotor model. This reference is defined as a discrete sequence of N pairs of airspeed and nacelle angle $(V, \beta_m)_i$ that belong to the allowed flight points region of the conversion corridor of Figure 1.

To represent the conversion from the helicopter configuration, i.e. a nacelle angle of 90 deg, to the airplane configuration, with a nacelle angle of 0 deg it is decided to assign $N = 9$ discrete points. The virtual pilot will fly the aircraft moving from one point to the other using the reference values as target.

To define the maneuver it is necessary to define a set of reference signal pairs, represented as vectors in $\mathbb{R}^N$, $(\mathbf{V}, \boldsymbol{\beta}_m)$ that are withing the conversion corridor and typically minimize a figure of merit J that can be computed performing the entire conversion simulation through the closed-loop LPV tiltrotor-pilot model.

In all simulation the angular rate $\dot{\beta}_m$ of the nacelle will be considered assigned and constant. Consequently, the time required to go from one point to the following one will be automatically computed starting from the nacelle angle step required during each segment. So if the nacelle angle step is

$$(\Delta\beta_m)_i = \beta_{m,i} - \beta_{m,i-1}, \tag{4}$$

the time required to run across each segment is

$$(\Delta t)_i = \dot{\beta}_m^{-1}(\Delta\beta_m)_i. \tag{5}$$

To avoid excessive accelerations in a segment the jump of velocity allowed during each step $(\Delta V)_i$ is limited in relation to the associated nacelle angle step $(\Delta\beta_m)_i$.

A typical tracking signal set is shown in table 1. In this case in the initial conversion up to 50 kn the acceleration is limited to 3 kn/s, while in airplane mode is limited to 5 kn/s.

The optimization is performed using the Genetic Algorithm implemented in MATLAB. The inclusion of

Table 1: Tracking signal for a typical conversion.

	segment									
Variable	1	2	3	4	5	6	7	8	9	10
V, kn	0	24	40	61	80	105	130	150	170	170
β_m, deg.	90	82	82	75	75	50	50	0	0	0
t,s	0	8	13.3	20.3	26.6	34.9	41.2	57.9	61.9	65.9

constraints on the optimization variables is enforced through a penalization approach.

Several different figures of merit J are considered as objective of the optimization, such as:

- minimization of the maximum rotor flapping angle reached during the maneuver, to minimize the associated bending moments on rotor blades;
- minimization of the pilot workload measured in term of control effort.

4.1 Tiltrotor Model

The starting element to develop the optimization process described in the previous section is the LPV model of the tiltrotor. To design the proposed methodology it has been decided to apply it to a classical tiltrotor model, the Bell XV-15, for which a large database of information is publicly available[16;17;18].

The complete model of the tiltrotor is built in MATLAB using MASST (Modern Aeroservoelastic State Space Tools), a tool developed at Politecnico di Milano for the aeroservoelastic and aeromechanical analysis of rotorcraft[19;20] and used already in several cases for tiltrotor modeling. The model developed in this case is composed by three elements: the rotors model, the airframe model and the control mixing unit that models the connection between the pilot stick inputs inserted in the cabin and the different control surfaces.

Since the conversion maneuver is a symmetric maneuver only the symmetric movements of the airframe have been considered: fore and aft, vertical translation and pitch rotation.

A CAMRAD/JA model of the tiltrotor is used to compute the trim conditions for all the flight conditions considered to build the set of linearized models. All the linearized models of the rotor are developed starting from CAMRAD/JA. The linearized rotor models are exported as time invariant multiblade models considering the two gimbal degrees of freedom plus the first out-of-plane bending collective mode to model the blade flapping; the cyclic and collective pitch modes plus the three rigid translations and rotations necessary to connect the rotor models to the airframe[19], and the 3 states due to the inflow model.

A complete database of aerodynamic derivatives of the airframe, including the appropriate modeling of the scheduling of flaperon position and the associated aerodynamic effect, together with the inertial properties of it are connected to the rotors to represent the airframe rigid body modes.

Finally, the connection between pilot stick input and controls is modeled, including a first order model of the actuators. In helicopter mode the stick movements are translated into longitudinal cyclic and collective pitch inputs to the rotors trough an ideal gearing system. In airplane mode the pilot inputs are transformed into elevator and collective pitch variations. During the conversion the center stick longitudinal displacement mixes the cyclic pitch variation with the elevator rotation. Consequently, it is required to change the gains of the longitudinal swashplate and elevator actuator continuously as function of the nacelle angle β_m. Additionally, it is required to introduce biases in the controls to reset the positions of cabin sticks and avoid ergonomic problems for pilots[16].

To perform a conversion, it is necessary to define, along the classical controls, the possibility to change the nacelle angle. In this case the nacelle rotation will be activated as a constant angular rotation of the rotors. However, the possibility to consider the nacelle angle as a dynamic control input transmitted by the pilot is not considered by the linearized models that are exported by CAMRDA/JA. However, linearizing the rotation of the nacelle it is possible to see that the rotation of the nacelle about a certain angular position corresponds to the in-plane translation of the entire rotor of a quantity $h = \beta_m r$ where r is the arm between the nacelle pivot point and the rotor center. Consequently, it is possible to extract the required stability derivatives and effects generated by a small nacelle rotation directly from the linearized rotor models.

The different linearized models are computed starting from the the following conditions: gross weight of 13000 lb, Sea Level Standard ISA conditions, straight level flight at load factor equal to 1.

A grid of flight conditions close to the conversion corridor is defined as scheduling variables, as shown in Figure 2. Using the CAMRAD/JA trim capability, the full trim states of the aircraft in each condition are computed and used as trim map for the qLPV model. This general state space realization together with the associated trim map compose the Jacobian qLPV model as describe by equation (3).

To tune the grid density it has been decided to use a linearized model to compute the trim input and

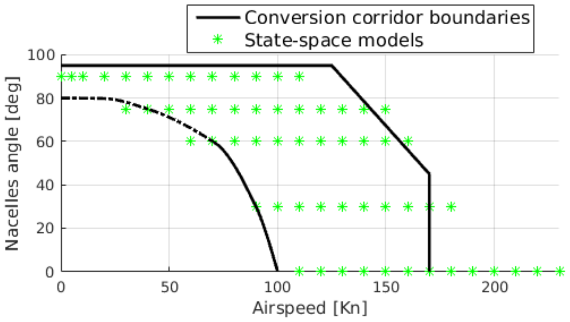


Figure 2: Linearized state-space models computed in the conversion corridor.

states required to move to another close flight condition. This was done both to move from one airspeed to another (higher and lower) and from one nacelle angle to another. For the speed a step of 10 Kts has been considered adequate, limiting the relative error to 10^{-2}. Only at very small speed in helicopter mode it was considered necessary to reduce the step to 5 Kts. For the nacelle angle a higher resolution was required at large angles close to helicopter mode, while a less dense resolution was deemed sufficient.

To improve the capability of the algorithm to model the aircraft close to the boundaries, some trim conditions outside the conversion corridor where considered, see Figure 2. However, not for all flight condition was possible to find a feasible trim condition.

When the scheduling parameters are located away from their grid locations an interpolation of the state space models is made by the LPV algorithm. A linear interpolation in the two dimensional airspeed nacelle angle is used in this case.

4.2 Virtual pilot model

The Optimal Control Model (OCM) proposed by Kleinman, Baron and Levison[21;22] in 1970 has been the first attempt to describe the behavior of the human pilot in a time domain optimal control framework. The OCM basic assumption is that the well-trained and careful human controller behaves optimally in some sense, adjusting the pilot's compensation for a given vehicle and task. The OCM has been widely used and has been validated in several tasks. The pilot model implemented in this work is derived from the Modied Optimal Control pilot Model (MOCM)[23] which is an improved version of the OCM. The MOCM retains the key aspects of the OCM such as a linear quadratic solution for the pilot gains with inclusion of control rate in the cost function, a Kalman estimator, and the ability to account for attention allocation and perception threshold effects. However, unlike the OCM, the structure of this model allows for direct calculation of pilot and system transfer functions. This MOCM pilot model together with pilot's effective time delay modeled through a second order Padé approximation, has been developed to obtain a realistic behavior of a virtual pilot able to stabilize the aircraft.

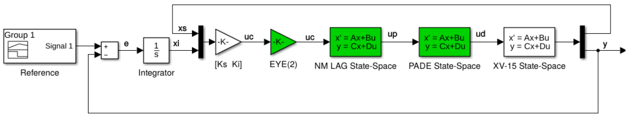


Figure 3: Block scheme of the virtual pilot model.

A Proportional Integrative outer control loop has been developed to add the ability to track the reference signal in terms of airspeed. Additionally an outer PI loop has been added to control the altitude, avoiding to increase or decrease significantly the altitude during the conversion maneuver.

As already stated, the nacelle angle has not been considered as a pilot input but rather an assigned input applied through a constant rate variation. A second order filter has been applied to this input to smooth out the irregularities associated with the transition from one segment to another.

5 LPV SIMULATION RESULTS

The first set of simulations are performed to look for the conversion sequence that allowed for a minimal rotor cyclic flapping. As figure of merit it has been chosen to minimize the integral of the cyclic flap angle during the maneuver. The assigned segments are those shown in table 1. The resulting path in the conversion corridor is show in Figure 4.

The values assumed by the module of the flap cyclic angle during the conversion is shown in Figure 5, where the flight velocity of 170 kts in airplane configuration is reached after 60 seconds. in this case and angular rate of 3 deg/s was considered with three nacelle angle holding transitions during the conversion at 82 deg and the at the two detents, 75 and 50 deg, see Figure 4. The flap angle shows a significant peak in the initial part of the conversion, that is essentially due to the required trim forces to be developed. This can be clearly understood by looking at the mapping of the trim cyclic flap angle required within the conversion corridor, shown 6, Consequently, a first strategy that could be considered optimal can be identified by looking for the rapid descent path on the trim cyclic flap diagram, as shown in figure 7. However, the results are disappointing as can be seen in Figure 8, because following this minimum path the initial part of the conversion keeps a high flap angle, while in the previous result the dynamics of the rotor leads to a faster reduction of the rotor cyclic flap angles.

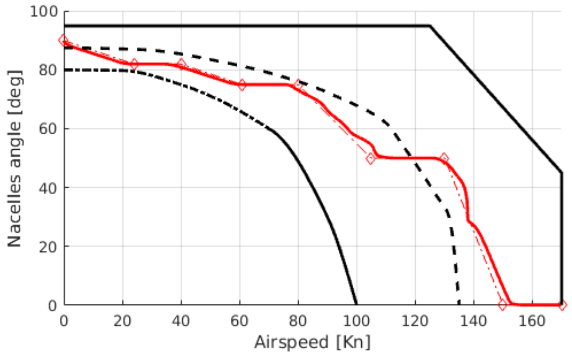


Figure 4: Typical path followed during the conversion maneuver.

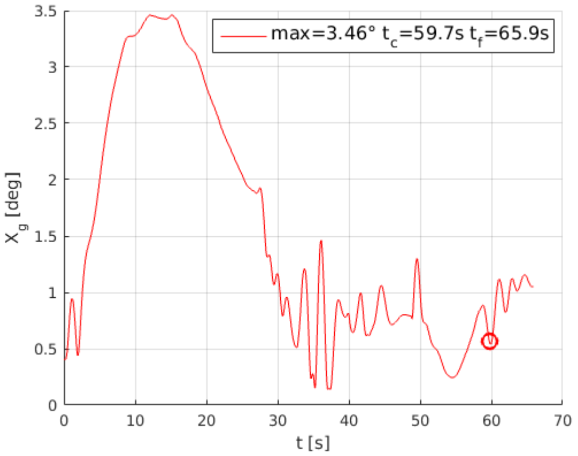


Figure 5: Cyclic flap angle during a typical conversion maneuver.

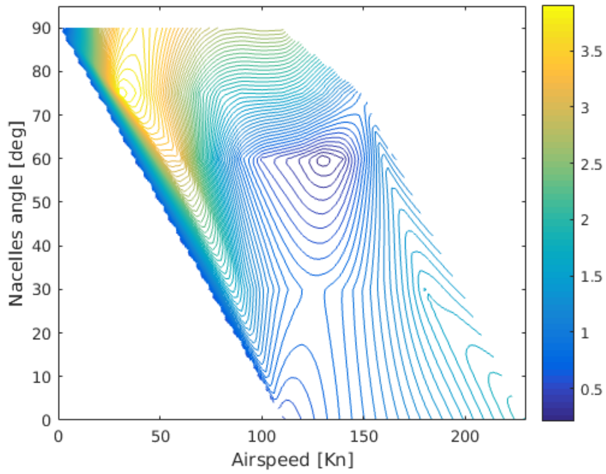
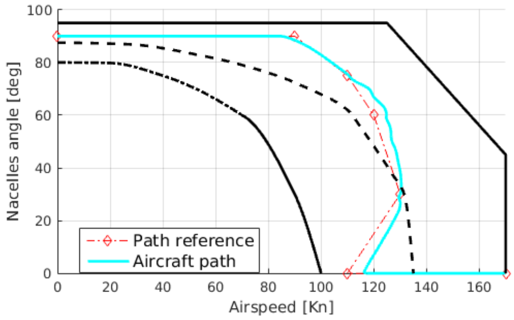


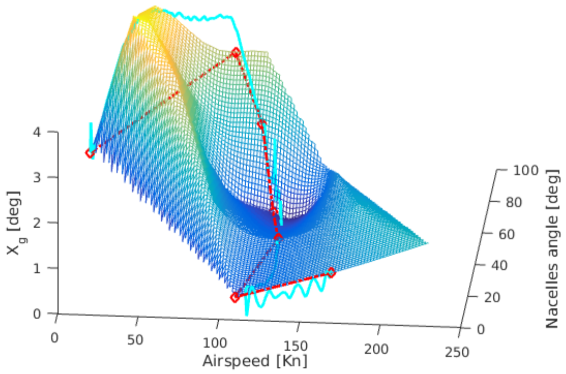
Figure 6: Mapping of the trim rotor cyclic flap angle.

The same maneuver can be performed using a rate of 8 deg/s, see Figure 9. In this case the oscillations of the flap angle are significantly larger, as shown in Figure 10.

It appear that pilots have the tendency to execute the maneuver staying close to the conversion corridor left boundary which represents the stall limit. This conversion path is reproduced in Figure 11. The controls in this case are characterized by a continuous reduction of the collective pitch in the initial part of



(a) 2D path



(b) 3D path

Figure 7: Minimum cyclic flapping angle path on conversion corridor.

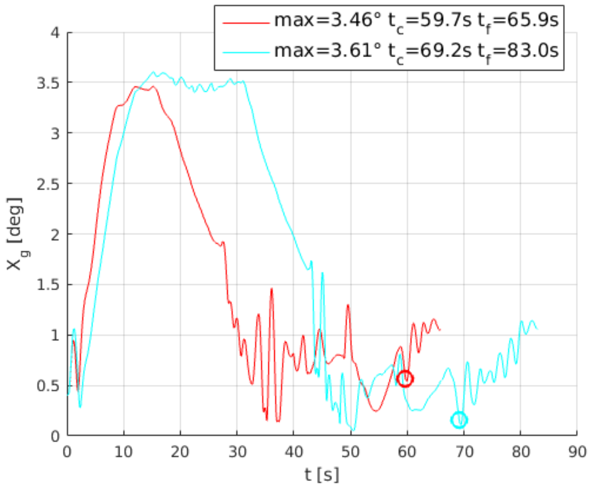


Figure 8: Cyclic flap angle along the minimum cyclic trim path.

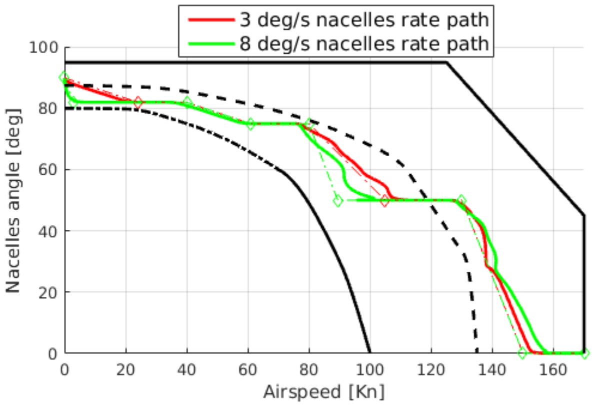


Figure 9: Conversion path at 8 deg/s.

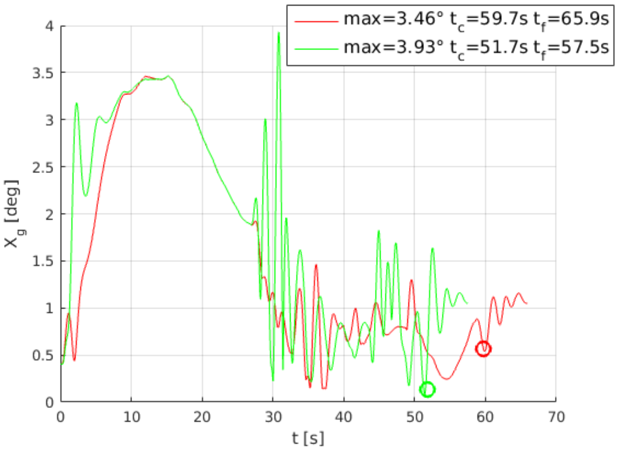


Figure 10: Cyclic flap angle during a conversion maneuver at 8 deg/s.

the maneuver, that is probably more ”natural” than the collective stick variation required in the reference maneuver shown before.

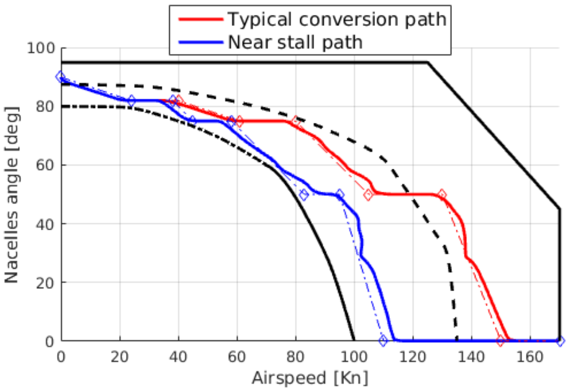


Figure 11: Near stall conversion path.

It is interesting to compare the optimal conversion maneuver obtained to what can be considered as the ”safest” conversion, i.e. the closest maneuver to the conversion corridor center line. To follow a path closer to the center line without increasing too much the aircraft acceleration it is necessary to slow down the conversion rate to 3 deg/s. In this case the conversion path is the one shown in Figure 13.

In this case the acceleration must be limited to a very small value during the seconds 42 and 58, see 14. In this case the control action is different but with a similar frequency content that the controls required during the typical conversion.

The same maneuver can be performed using an automatic nacelle angle control system to adapt the nacelle angular rate during the conversion. The conversion path is shown in Figure 15. The required, variable, nacelle angular rate is shown in Figure 16, where it is shown that the maximum rate is close to 12 deg/s, for a short period of time. In this case the flap angle shows larger oscillations in the final part of the maneuver due to the larger angular rate required, Figure 17, and the control effort required is somehow higher, Figure 18. Hover the time to perform the conversion is smaller.

6 CONCLUSIONS

This paper presented a first effort to use LPV models to better understand the conversion maneuver. This effort could be exploited in order to design the logic of an automatic nacelle control system. A more thorough exploration of the possible conversion path will be performed in the future together with the extension to more detailed numerical model of the tiltrotor including all the other elastic degrees of freedom omitted in this preliminary effort.

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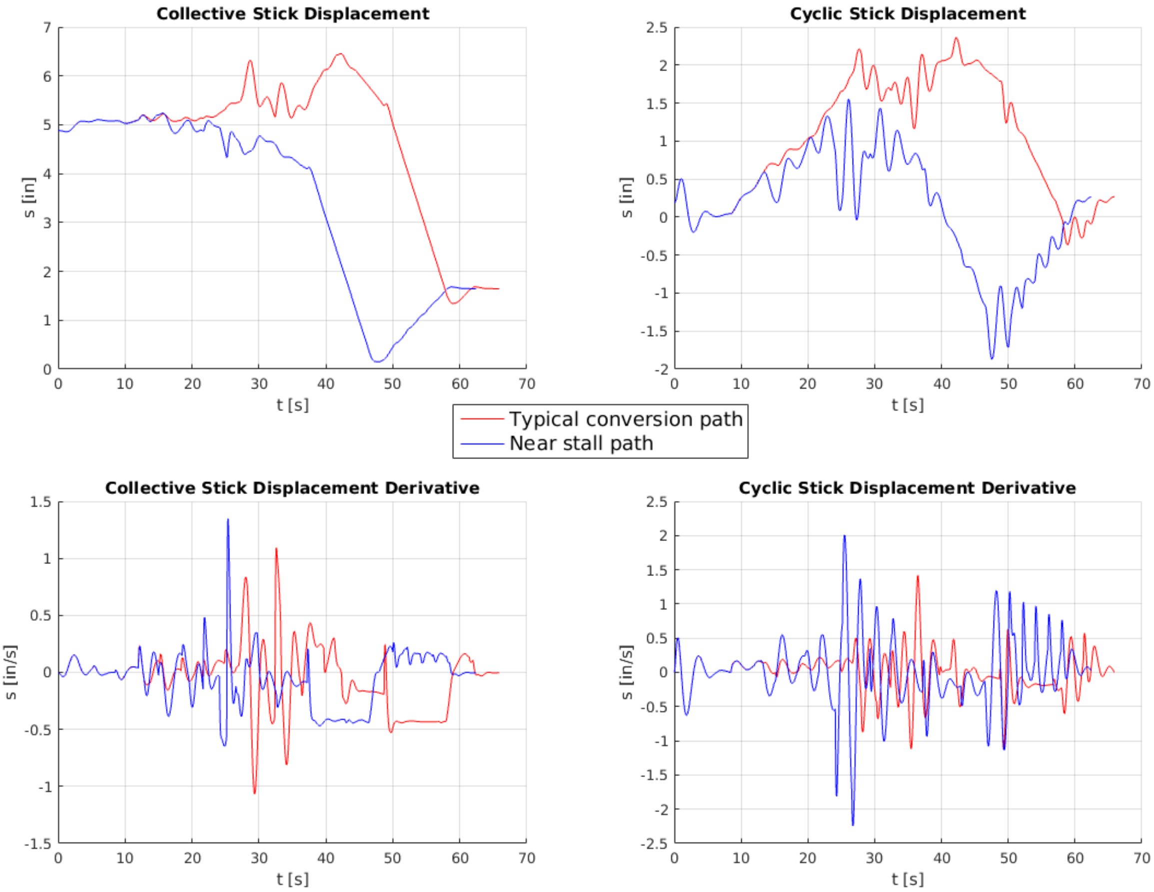

Figure 12: Near stall conversion command histories.

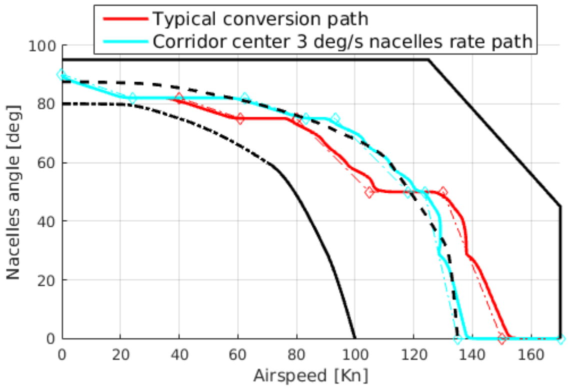

Figure 13: Conversion path close to the center line at a constant conversion rate at 3 deg/s.

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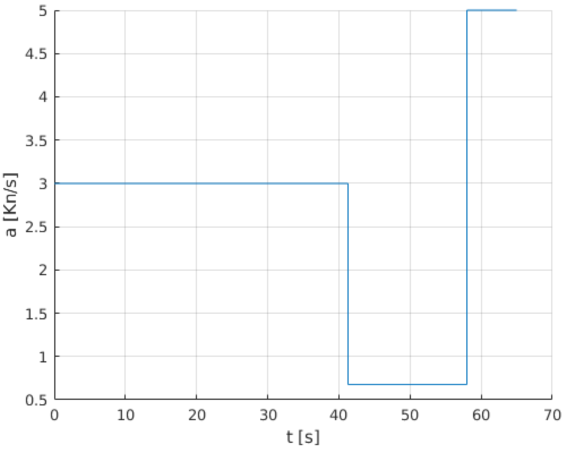

Figure 14: Aircraft acceleration profile during conversion at 3 deg/s.

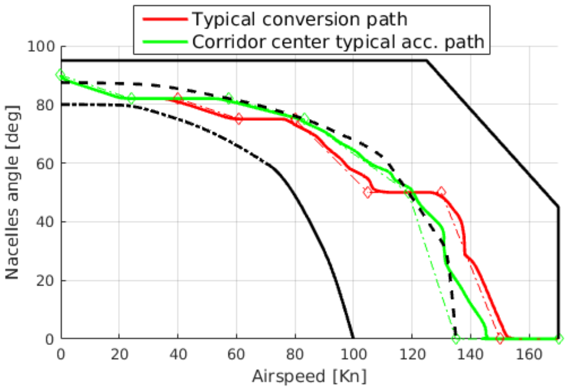

Figure 15: Conversion path close to the center line at a variable conversion rate.

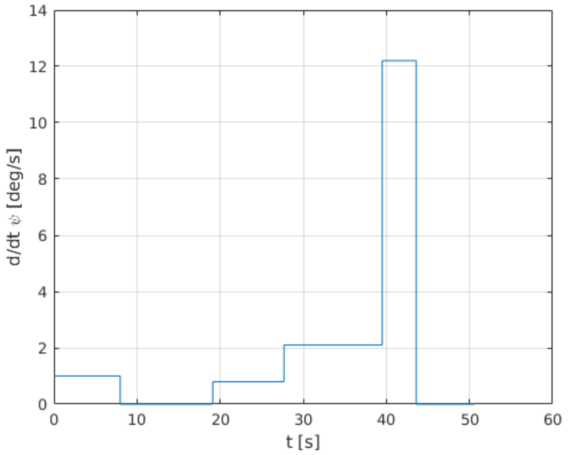

Figure 16: Nacelle angular rate for the conversion close to center line.

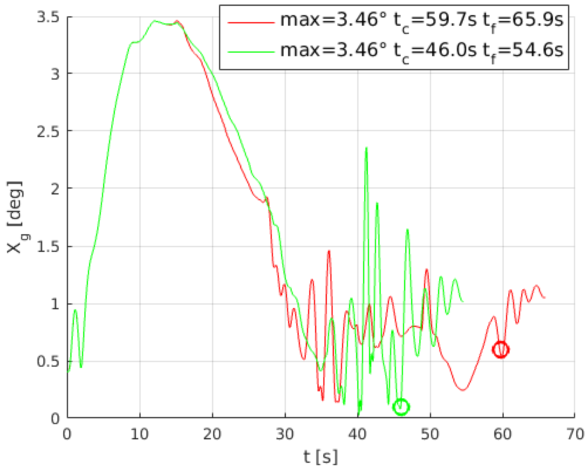

Figure 17: Cyclic flap angle during a conversion maneuver along the center path.

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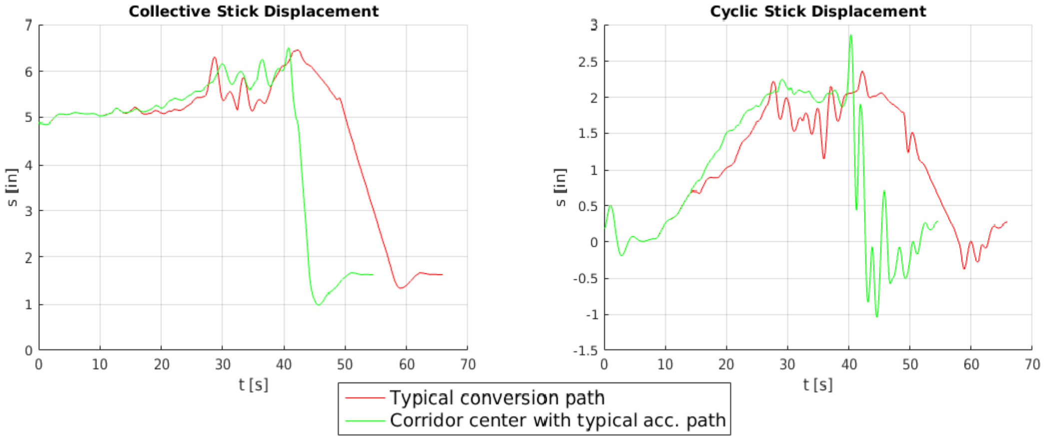

Figure 18: Control input to follow the conversion corridor center path.

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