DEVELOPING AN OBSERVATION METHODOLOGY FOR NON-MEASURABLE ROTORCRAFT STATES

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Abstract

A recurring problem in engineering is that of observing quantities which cannot be directly acquired through a measuring instrument. For the case of rotorcraft, such quantities include the thrust coefficient and the angle of attack of the tip-path plane. These variables can be profitably exploited to predict the acoustic footprint of the vehicle on the ground, thus helping in designing and monitoring appropriate approach maneuvers, suitable for reducing perceived noise for overflown communities. In previous works on the topic, it was shown how to construct an observer based on real-time measurements of rotor flapping and a few other aeromechanical quantities, capable of estimating key unmeasurable parameters, with an airspeed-scheduled linear structure. Theoretical support comes from a very straightforward model of the helicopter flight mechanics and of the blade flapping motion. Testing on the proposed observer have been carried out during specific descent profiles only, showing the validity of the concept. The present paper tries to expand the analysis to a wider array of test cases, emending the original design in the process. In particular the analysis is extended to a broader spectrum of airspeeds, coping with the non-linear behavior of rotorcraft flight mechanics and rotor flapping dynamics. The effect of an augmentation of the array of measures with more parameters commonly available from the helicopter data bus on the performance of the observer is quantified. The chance to obtain further observed measures, in particular the sideslip angle, from the same set of measurements is considered. Finally, the observer is tested in off-design conditions, in order to assess its robustness under more general conditions than descents. The work is supported by several results obtained in a high fidelity virtual environment.

1 INTRODUCTION

Noise pollution is a major concern in the field of aeronautics. In the case of rotorcraft, substantial research efforts have tried to work out solutions following either a control or a monitoring approach. For the first, control systems aimed at the suppression of the main sources of noise (the rotors and the engine nozzles) through dedicated active or passive devices, or design criteria of the interested components such to reduce noise emissions have been proposed. While many solutions inspired by this approach can be found in the literature, a major shortcoming appears to be the lack of generality of the proposed design procedures, and the high level of complexity of controllers for noise abatement [1, 2, 3, 4, 5, 6, 7, 8]. The second approach has been focused on the design of a system to report to the pilot suitable information on the noise footprint of the helicopter during critical maneuvers such as approach and landing. This would allow the pilot to carry out a maneuver especially targeted at reducing perceived noise. Recent research efforts within the MANOEUVRES Clean Sky project [9] demonstrated that such a system can be designed. Key measurements for feeding it include the angle of attack of the main rotor tip-path plane (TPP-AOA), the main rotor thrust coefficient and the advance ratio of the rotorcraft [10, 11]. These quantities cannot be measured directly, but as documented in [11, 12] an observation of these variables is indeed possible, mainly based on the knowledge of the flapwise motion of the blades of the main rotor, following an approach introduced in [13]. The observation approach documented in [12] proceeds starting from a theoretical analysis, where a system of equations for the dynamics of the rotor is presented, and a theoretical support for the feasibility of the observation system is derived by manipulation of a widely accepted model [14]. The outcome of the analysis is a linear structure of the observer, where the observed variables are obtained from basic measures of flight mechanics quantities and of the flapwise motion of the rotor. In practical terms, the parameters of the observer have been obtained recurring to a model identification procedure, carried out starting from ad-hoc simulations performed in virtual environment.

The present paper is focused on the development of the observer proposed in [12], which assumes the availability of on-board measurements of the rotor flapping motion, as allowed by the recently developed rotor state measurement system described in [15, 16].

The considered additions to the previous analysis include three main elements. Firstly, in order to increase the accuracy of the observer under design test conditions – i.e. descent trajectories – the array of measurements has been augmented with the value of the tail rotor collective. The knowledge of this quantity is provided to the observation algorithm especially in order to ameliorate its capacity to deal with sideslipped approach conditions, thus ensuring a better accuracy in presence of a non-null sideslip angle. The performance of the observer is tested over a wider array of airspeeds, spanning over the operating envelope of the machine.

In a second stage, the chance to observe more variables from the same array of measurements is investigated. In particular, the angle of attack of the fuselage and the sideslip angle are considered.

Finally, the observer is tested in off-design conditions, adopting test maneuvers very different from those considered in the identification phase, representative of possible disturbances to constant-speed straight descents.

Many quantitative results will be presented, obtained in virtual environment from the numerical model of an existing testbed.

2 AUGMENTING THE MEASUREMENTS

The original shape assumed for the observer in [12] allows to reconstruct the values of the main rotor tip-path-plane angle of attack α_{TPP} and thrust coefficient C_T, starting from the knowledge of the five quantities a_0, a_{1s}, b_{1s}, ρ and W, representing the rotor coning, the longitudinal and lateral cyclic flappings, air density and the gross weight of the helicopter, respectively. The postulated linear form of the observer can be written as

(1) $$\boldsymbol{s} = \boldsymbol{T}(\mu)\boldsymbol{m} + \boldsymbol{q}(\mu),$$

where $\boldsymbol{s} = \{\alpha_{\mathrm{TPP}}, C_T\}^T$ is the array of observed quantities and $\boldsymbol{m} = \{a_0, a_{1s}, b_{1s}, \rho, W\}^T$ the array of measurements. It can be seen that both matrix $\boldsymbol{T}(\mu)$ and array $\boldsymbol{q}(\mu)$ are functions of the advance ratio μ, recalling the dependence of these quantities on the airspeed of the rotorcraft [12, 14].

In order to find the matrices of the observer, an approach based on parameter identification can be adopted. In practical terms, the helicopter model is flown on assigned flight profiles, controlled by means of a suitable control law, and both the observed and measured quantities are collected at an assigned frequency during the simulation. The corresponding N samples are collected in matrices yielding

(2) $$\boldsymbol{S} = [\boldsymbol{s_1} \quad \boldsymbol{s_2} \quad \dots \quad \boldsymbol{s_N}]$$

(3) $$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{m_1} & \boldsymbol{m_2} & \dots & \boldsymbol{m_N} \\ \boldsymbol{1} & \boldsymbol{1} & \dots & \boldsymbol{1} \end{bmatrix}$$

such that

(4) $$\boldsymbol{S} = [\boldsymbol{T}(\mu) \quad \boldsymbol{q}(\mu)]\boldsymbol{M}$$

and the values of the parameters can be estimated using a least-squares method [12, 13]. Since the observer model is bound to an assigned airspeed, samples are collected during simulations in range of airspeeds around a reference value. These samples are used to synthesize a model for that reference airspeed. The span of the airspeed range around the reference should be chosen considering that a value too small would produce a model that is finely tuned for a precise airspeed, but would potentially worsen the reconstruction of $\boldsymbol{s}$ for an airspeed value even slightly out of the range. On the other hand, conveying samples from too wide a range into a same model would make the model generally less accurate, due to the non-linear behavior of the physics, which would not appropriately taken into account.

In order to cope with a changing airspeed in the observation phase, the coefficients of the observer are linearly interpolated as functions of the actual value of the advance ratio, lying between two reference airspeeds.

By inspection of the quality of the measured signals in $\boldsymbol{m}$ from simulations in [12], it may be speculated that a better knowledge of the lateral-directional state of the helicopter would be beneficial for the accuracy of the estimation. A way to provide such information starting from quantities already available from the avionic data bus of the helicopter – thus without making the sensor chain more complicated – has been found in the augmentation of $\boldsymbol{m}$ with the tail rotor collective θ_{TR}. The simplest way to add this quantity to the array of measurements, similarly to what had been done already for the quantities ρ and W, is that of supposing a linear behavior of the observation model with respect to it, yielding

(5) $$\boldsymbol{m^{aug}} = \{a_0, a_{1s}, b_{1s}, \rho, W, \theta_{\mathrm{TR}}\}^T.$$

This in turn allows to preserve the identification approach based on a linear, airspeed-scheduled scheme, to synthesize the observer, Eq. (4).

Results on the effect of the augmentation will be presented in a later section of the paper, assessing also the robustness of the observation chain through simulations in off-design conditions.

3 INCLUDING MORE OBSERVED QUANTITIES

A further development of the proposed observer is the augmentation of the array of observed quantities $\boldsymbol{s}$. Albeit not strictly necessary to the aim of monitoring the noise footprint on the ground, the angle of attack of the fuselage α_{fus} and the sideslip angle β have been deemed relevant for their use in automatic flight controllers and possibly for trajectory monitoring/prevision tasks.

The addition of the tail control variable θ_{TR} to the array of measurements, which grants a better knowledge of the lateral-directional attitude of the rotorcraft, allows to reconstruct the value of the sideslip angle β with good accuracy.

For the observation of β there is no need for any further augmentation of the array of measurements $\boldsymbol{m}$, which retains the structure shown in Eq. (). The shape of the observer also for the new observed quantity is supposed linear, thus preserving the analytic form in Eq. (3).

To the aim of identifying the model including the new observed state β, it is necessary to include more simulations in the pool considered for model synthesis, adding a set with different values of the new quantity of interest.

The value of the angle of attack of the fuselage α_{fus} is obtained more easily than β, exploiting the definition

(6) $$\alpha_{fus} = \alpha_{\mathrm{TPP}} + i_w - a_{1s},$$

where it is assumed that the longitudinal cyclic flapping at the first rotor revolution frequency a_{1s} be representative of the overall oscillation of the blade during a revolution – higher harmonic terms are not accounted for, as typical [13]. In Eq. (6), i_w represents the angle between the axis of the main rotor shaft and the fuselage roll axis.

Assuming that i_w is an assigned geometrical quantity, the accuracy in the estimation of α_{fus} depends only on the quality of the measure of the flapwise motion a_{1s} and of the observation of α_{TPP}.

Results from the proposed developments of the observer will be presented in a dedicated section.

4 RESULTS

Similarly to [12], the observer has been developed and tested in virtual environment using the simulator RSim [17]. This implements a rigid model suitable for analyzing the flight dynamics of the helicopter, plus a model of the flexible main rotor based on the theory found in [18]. The simulator is coupled with a dedicated library of maneuvers which can be used to fly the rotorcraft through complex trajectories. The set-point for each section of the maneuver is followed through guidance routines, which implement PID controllers governing the main rotor collective, lateral and longitudinal cyclic and the tail rotor collective based on the values of key quantities in each selected maneuver.

The control and simulation suite can be used for running simulations aimed at the synthesis of the observer, and for verification of the synthesized observer as well.
The validated model of an existing medium lift helicopter has been considered for all tests.
Due to the intended application of the observer to descent trajectories, the design maneuver considered in the analysis is composed of a descent flight with constant descent angle, flown at constant airspeed.
Values for the airspeed V of 30, 40, 50, 60, 70, 80, 100 and 120 kn are considered, spanning over the typical operational range of the rotorcraft during standard descents. The considered descent angles γ span between 3 and 7 deg, with 1 deg increments. The trajectories have been flown at weights W between 68.7% and 100% of the MTOW, with 3.1% increments. The weight of the rotorcraft has been supposed constant during all simulations, which is acceptable due to their short time span. In order to study the effect of asymmetric flight, values for the sideslip angle β of 0, -10 and +10 deg have been considered for identification.

4.1 Augmentation of the Measurement Array

4.1.1 Identification Quality

In order to check the quality of the identification, the observer synthesized from samples corresponding to an assigned reference airspeed is checked with respect to the very same samples. Figure 1 shows the result of this analysis for the case of α_{TPP} and for an example speed V = 50 kn. Each sample is represented by a marker on the plot. The greater the distance from the ideal correlation line (the red bisecting line), the worse the estimation.
It is noteworthy that, differently from the other quantities previously considered in the array of measurements $\boldsymbol{m}$, the quality of θ_{TR} is that of an input variable. Due to the dynamics of the controller, this variable may be more oscillating during adjustment maneuvers, and typically ahead of phase with respect to the rotor states a_0, a_{1s} and b_{1s}, which are part of the helicopter response.

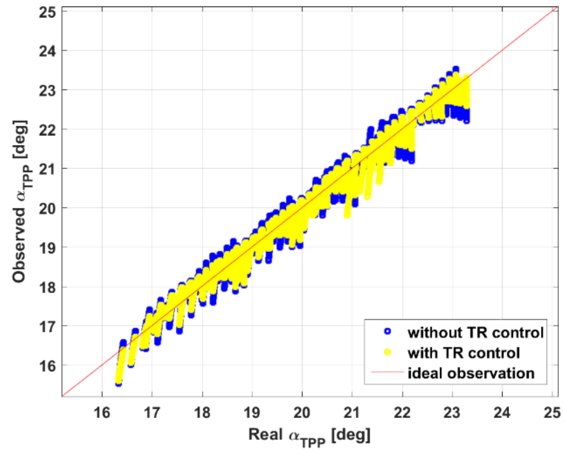

Figure 1: Observation quality test on α_{TPP} at V = 50 kn. Comparison between augmented and standard model.

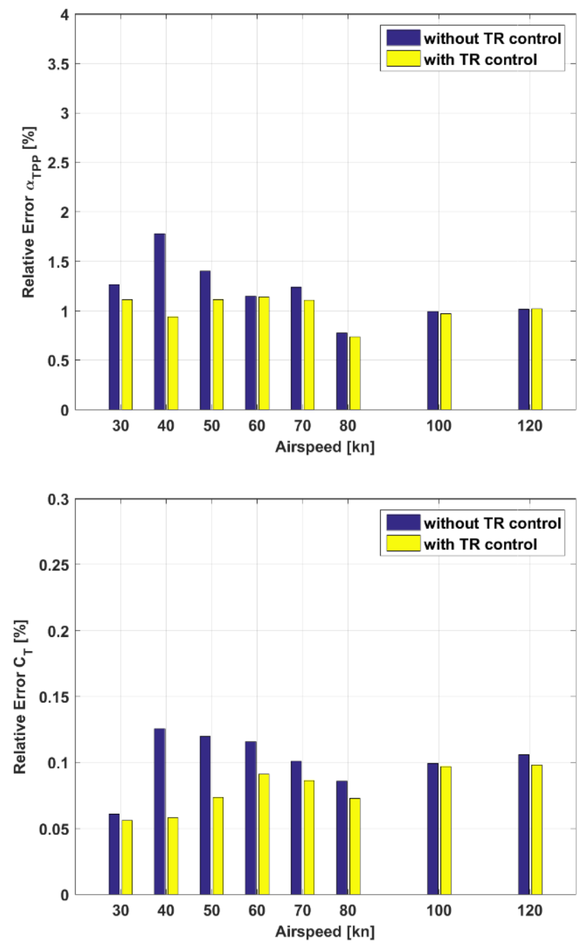

Figure 2: Percent observation error on the samples used for identification, as a function of the airspeed. Comparison between augmented and standard model. Top plot: α_{TPP} . Bottom plot: C_T.

For these reasons, while on one side improving the knowledge of the helicopter flight condition as desired, the selected variable may have to a certain degree a polluting effect in the observer synthesis phase. Notwithstanding this fact, from the plot it is easy to see that the proposed augmentation of the array of measurements with the tail control value θ_{TR} has a beneficial effect on the accuracy of the synthesized model.

In order to provide a measure of the effectiveness of the augmentation of the observer with θ_{TR}, the average quadratic error from all samples has been used as a measure of accuracy of the observation.

Starting from the analysis in Figure 1, the error for all considered airspeeds for both α_{TPP} and C_T can be computed, and the plots in Figure 2 are obtained.

From both plots the positive effect obtained through the augmentation of the array of measurements is apparent. In particular, a beneficial effect is felt more in the lower part of the spectrum of airspeeds. The error on C_T is always very low, considering both different speeds and compositions of the array of measurements. This behavior is typical to all other analyses considered in this work, therefore, for the sake of brevity, displaying results for C_T will often be avoided in the following.

4.1.2 Observation Results

The observer based on the augmented array of measurements has been tested on samples that were not considered in the identification phase. Figure 3 shows the results of an observation in descents with sideslip angles β of -5 and +5 deg, for all considered airspeeds and weights.

The contribution of the new measurement to the overall accuracy, represented here by the average square error on α_{TPP}, is positive in the lowest part of the airspeed spectrum, whereas its effect is less beneficial, or even a little worsening, at higher speeds.

The mixed quality of the contribution of this control variable to the accuracy of the observation may be explained looking at the sensitivity of the trimmed value of θ_{TR} over the airspeed spectrum of the considered helicopter.

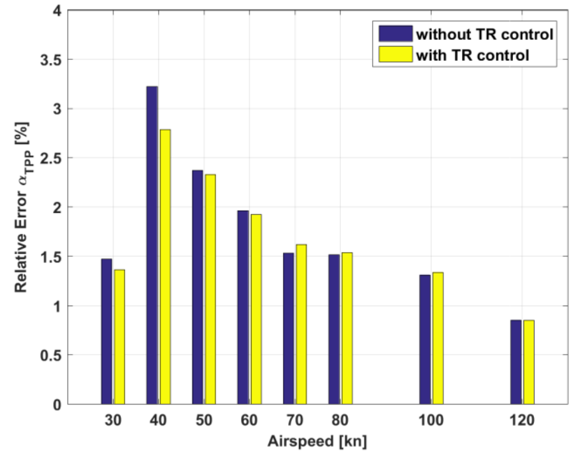

Figure 3: Percent observation error on α_{TPP} for changing airspeed. Check on sideslip values not used for identification.

From Figure 4 it is possible to see that the sensitivity, i.e. the slope of the curve with respect to the airspeed, is much higher between 30 and 50 kn than between 60 and 120 kn. Correspondingly, the effectiveness of the measure of θ_{TR} in helping to distinguish between different sideslip angles will be lower in the higher part of the airspeed spectrum considered in Figure 3. The sensitivity is increasing again close to 120 kn, and the contribution of the new measure tends to be again positive for that speed, and possibly over it.

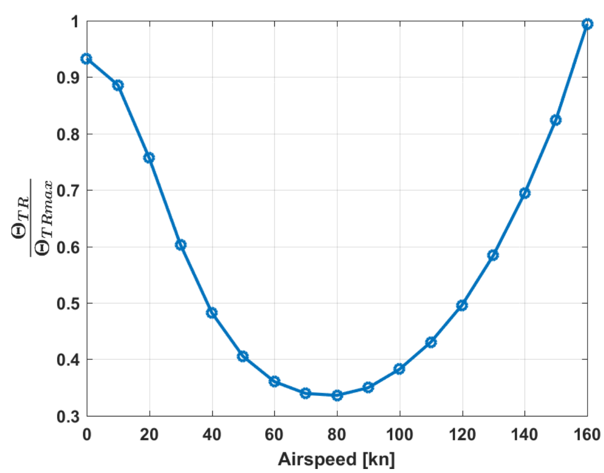

Figure 4: Normalized value of θ_{TR} for trim as a function of the airspeed.

However, the level of accuracy remains largely similar to that obtained with the non-augmented set of measurements even in the worst considered case.

In order to test the effect of the adopted scheduling strategy, the observer has been tested on samples collected during descents at intermediate airspeeds between the reference nodal values, for a null sideslip angle. Figure 5 presents a comparison of the average square error on α_{TPP}, for different intermediate speeds, showing the effect of the augmentation of the array of measurements.

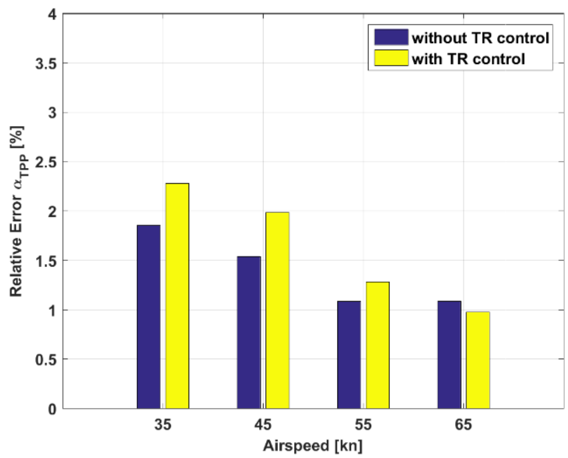

Figure 5: Percent observation error on α_{TPP} for changing airspeed. Check on airspeeds not used for identification.

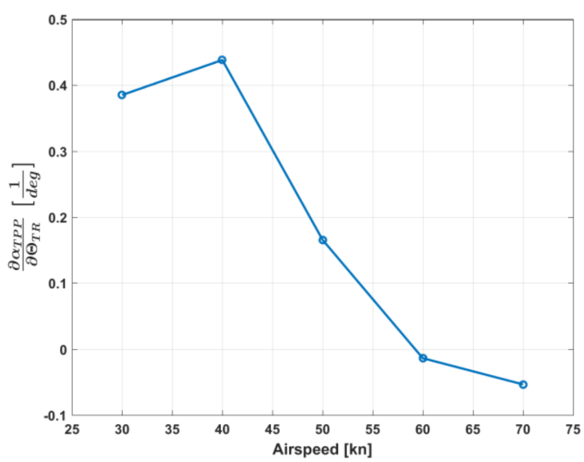

Figure 6: Dependence of the model coefficient $\frac{\partial \alpha_{\mathrm{TPP}}}{\partial \theta_{\mathrm{TR}}}$ on the airspeed.

It can be seen that, while the values of the accuracies are largely similar, there is a little disadvantage in using an augmented measurement array. This can be ascribed to the strong non-linearity of the sensitivity $\frac{\partial \alpha_{\mathrm{TPP}}}{\partial \theta_{\mathrm{TR}}}$ with respect to the airspeed. This sensitivity represents the coefficient in the model matrix $\boldsymbol{T}(\mu)$ relating α_{TPP} to θ_{TR}.

Figure 6 is a plot of how this coefficient changes with airspeed. Especially in the extreme operating regions of the envelope, it can be noticed that the behavior is considerably non-linear.

The use of a linear interpolation between nodal values constitutes a potential source of error, which in this case can be dealt with through a finer discretization with respect to the airspeed.

4.1.3 Observation in Off-Design Conditions

In order to assess the robustness of the observer with an augmented measurement array, two off-design test cases have been considered.

These have been chosen to analyze the most likely perturbations to a descent, i.e. errors on the airspeed and those ensuing from adjustments of the trajectory.

The first test case is a decelerated descent, where the value of the airspeed is changed between pre-determined values along a descent path with a constant slope. As a result, the value of α_{TPP} will be increasing along the trajectory. Figure 7 shows the results obtained from two such decelerated descents at assigned weight, between 50 and 30 kn, and between 70 and 50 kn.

In this case the effect of the augmentation of the array $\boldsymbol{m}$ is beneficial on the accuracy, in both cases of α_{TPP} and C_T, for the deceleration in the lower part of the operating spectrum. On the other hand, the effect of the new measure in a deceleration between higher airspeeds, between 70 and 50 kn, is negligible on α_{TPP}. This is in line with the lower contribution of the control input θ_{TR} to the accuracy of the observer of α_{TPP}, already noted in Section 4.1.2.

The second off-design maneuver considered is a coordinated turn. Airspeeds of 30, 50 and 70 kn are considered, together with turning rates of 3, 6 and 9 deg/s. These are not aggressive maneuvers, yielding a maximum load factor of 1.16, and are configured to isolate the effect of a lateral disturbance to a reference descent. Figure 8 shows the results on the accuracy of the reconstruction of α_{TPP} in the considered cases.

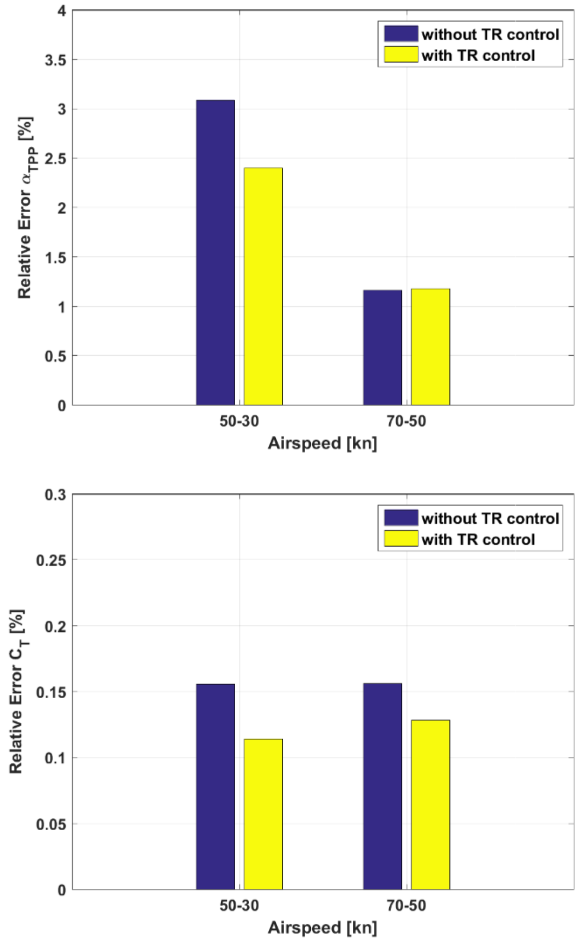

Figure 7: Percent observation error in off-design decelerated descents, as a function of the airspeed. Comparison between augmented and standard model. Top plot: α_{TPP} . Bottom plot: C_T.

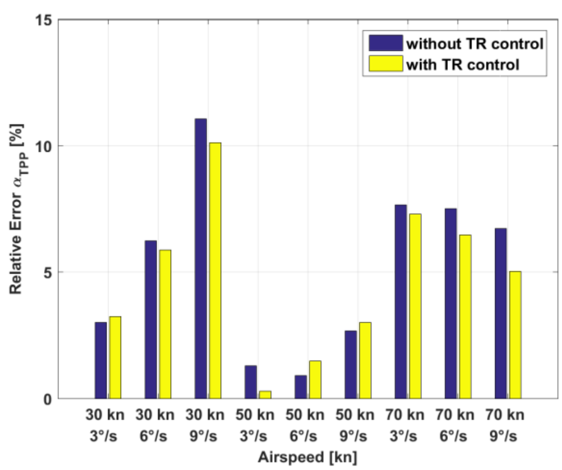

Figure 8: Percent observation error on α_{TPP} in off-design coordinated turns, for changing airspeed and turn rate. Comparison between augmented and standard model.

Again the augmentation of the array of measurements guarantees an increase in accuracy for the highest and lowest airspeeds in the operating spectrum, whereas it is not advantageous for intermediate airspeeds (50 kn).

4.2 Observing the Fuselage Sideslip Angle

4.2.1 Identification Quality

The addition of β to the array of observed quantities has been preliminarily tested with an analysis of the reconstruction on the same samples considered for identification. This has been performed on the same pool of simulations considered for the identification of the observation models analyzed in Section 4.1. In particular, values for β of 0, -10 and +10 deg have been considered, as explained at the beginning of Section 4. An analysis similar to that presented in Figure 1 is shown on Figure 9.

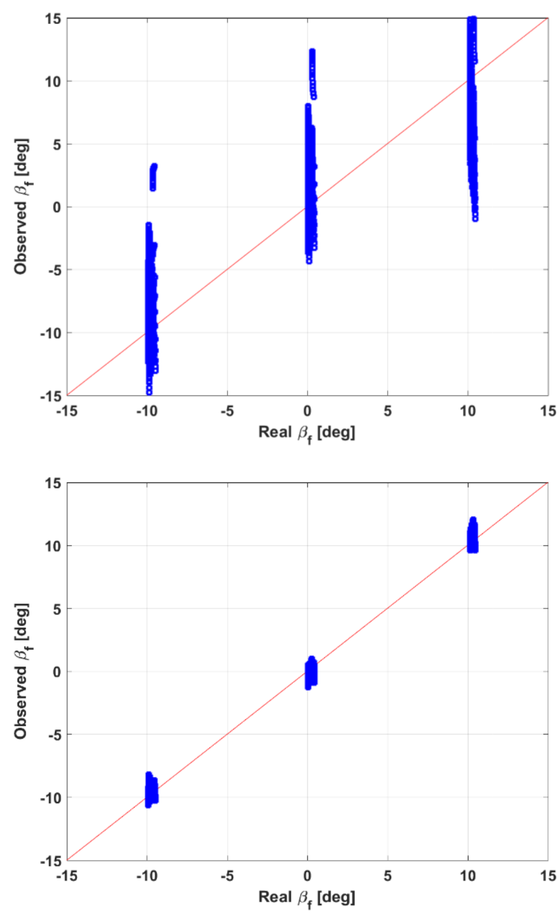

Figure 9: Observation quality test on β at V = 50 kn. Comparison between standard (top plot) and augmented model (bottom plot).

The top subplot shows the result of the observation in case the array of measurements $\boldsymbol{m}$ is not augmented with the tail control input θ_{TR}, whereas the bottom plot shows the result of the augmentation. The figure refers to a speed of 50 kn and to all considered weights.
By comparing the plots it is immediately apparent that the presence of θ_{TR} in $\boldsymbol{m}^{aug}$ plays a major role in the observation of β, which turns basically impossible without the information provided by the tail control variable.

4.2.2 Observation Results

Similarly to Section 4.1.2, the observer in the new structure has been tested on samples not used for the identification. In particular, new samples have been collected from simulations at β values of +5 and -5 deg, for all weights and for all airspeed considered in the identification phase. Figure 10 shows the results of this test phase, in terms of the average square error on β for the considered airspeeds.

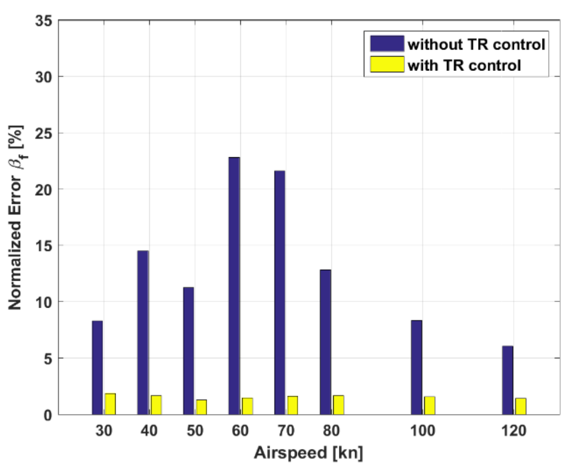

Figure 10: Percent observation error on β for changing airspeed. Comparison between augmented and standard model. Samples not used for identification.

Similarly to Figure 10, the effect of the presence of θ_{TR} in $\boldsymbol{m}$ can be deemed strictly necessary to obtain a good observation result. Provided this quantity is available, the observer performs very satisfactorily, with a performance similar to that obtained on α_{TPP} with the observer in its original form [12].

4.2.3 Observation in Off-Design Conditions

In order to assess the robustness of the observer for β, a set of decelerated descents have been considered, defined similarly to Section 4.1.3, between 50 and 30 kn and between 70 and 50 kn.
In Figure 11 the results corresponding to these decelerations are reported, considering an observation both with and without θ_{TR} among the measurements.
Whilst it is once more evident that θ_{TR} should be used in order to obtain acceptable observation results, the observer shows a very good performance also in slightly off-design conditions, thus assuring a good reliability of the proposed system in presence of mild airspeed disturbances.

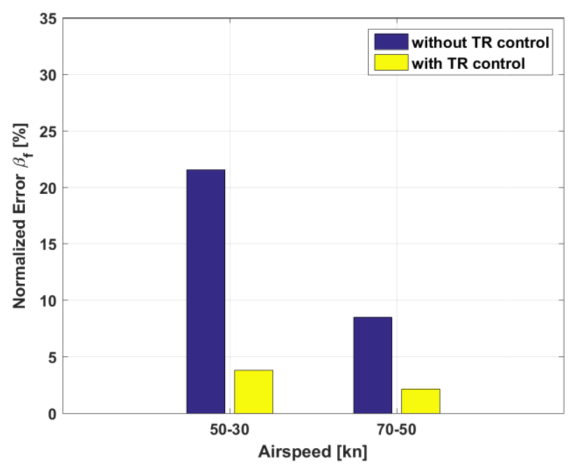

Figure 11: Percent observation error on β in off-design decelerated descents, as a function of the airspeed. Comparison between augmented and standard model.

4.3 Observing the Fuselage Angle of Attack

As already commented in Section 3, the accuracy in the estimation of the angle of attack of the fuselage α_{fus} will depend strictly on the precision in the reconstruction of α_{TPP} and of the measurement of a_{1s}, which is considered free of any noise in the present analysis. This effect can be further appreciated looking at Eq. (6).

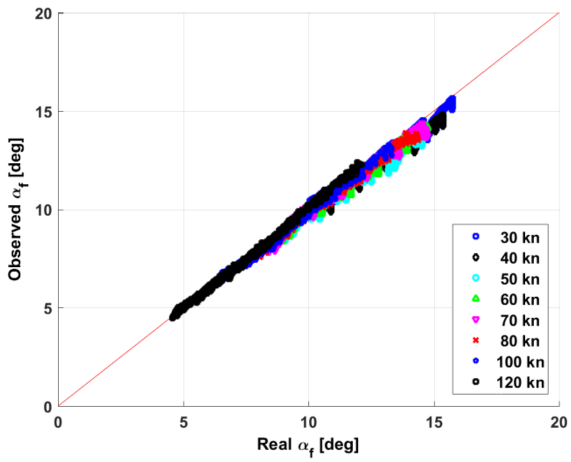

Figure 12: Observation quality test on α_{fus} at several airspeeds.

Due to the generally good results in the reconstruction of α_{TPP}, shown in [12] as well as in the present work, the accuracy in the observation of α_{fus} can be reasonably expected to be good.
Following the scheme of Figure 1 and Figure 9, Figure 12 shows the results of the measure of α_{fus} for all considered test airspeeds, for conditions with β of 0, +10 and -10 deg and for all considered weights. With an eye-norm it is easy to notice that all markers fall very close to the ideal correlation line, confirming that no critical issues should be expected in the observation of α_{fus}.

5 CONCLUSIONS

In this work, the potential of an observer originally developed for the main rotor tip-path-plane angle of attack and thrust coefficient has been further investigated, trying to exploit possible areas of development. In particular, the effect of the augmentation of the array of measurements including the tail collective control has been studied, considering a wider array of airspeeds covering the operating envelope of the considered testbed. The accuracy of the observer is significantly increased with respect to the original version, especially at lower airspeeds. A potential critical point of the formulation has been found in the high sensitivity of the model coefficients to the airspeed, which can be tackled by increasing the number of airspeed nodes considered for the identification of the observation model.

The chance to expand the array of observed quantities without further increasing the number of measures has been investigated next. It was found that the angle of attack of the fuselage can be easily estimated from quantities measured or already considered as output of the observation. Furthermore, the sideslip angle of the fuselage can be effectively observed when the tail rotor collective is included in the array of measurements.
Finally, the observer has been tested in off-design conditions to assess its robustness with respect to disturbances to a standard descent trajectory. Deceleration and turns were considered as test cases. The corresponding accuracy rating has been deemed adequate for the intended scope of the observer.

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