COB-2021-2163 SYNTHETIC ESTIMATION OF ANGLE OF ATTACK AND SIDESLIP USING A MANEUVER RECONSTRUCTION METHOD FOR FLIGHT TESTING OF AN UAV

Andrew Gomes Pereira Sarmento
Alain Giacobini de Souza
Luiz Carlos Sandoval Góes
Roberto Gil Annes da Silva
Laboratório de Sistemas Aeronáuticos (LSA)
Instituto Tecnológico de Aeronáutica (ITA)
Praça Marechal Eduardo Gomes, 50 Vila das Acácias, 12228-900, São José dos Campos/SP-Brasil
andrewgp@ita.br, giacobin@ita.br, goes@ita.br, gil@ita.br

Abstract. With the growing development of remotely piloted aircraft, there is a need to identify aerodynamic parameters for future use to optimize control loops, making it possible to carry out autonomous missions. Due to the high cost of anemometric instruments and the low load capacity of the aircraft, there was a need to study methods for estimating the main anemometric data used in the identification process, the angles of attack, and sideslip. The main objective of this research is to estimate the angles of attack and sideslip of an Unmanned Aircraft Vehicle (UAV) and to observe the quality of this estimate comparing with the results measured by the instrumentation on board. The platform used was the UAV C2, equipped with the MicroPilot LRC 2 autopilot system for the provision of inertial data, GNSS, and relative speed, as well as a probe for the supply of data on the angles of attack and sideslip. The estimation of the angles comes from the maneuver reconstruction using the equations of the dynamic model. Once the attitude variables, angular velocities, and accelerations are effectively measured, rewrite the equations of the dynamic model as a function of the variables measured in the gravitational center of the aircraft. In-flight data are implemented in the equations for numerical integration, but due to bias errors in the accelerometers and drift in the gyroscopes, after the integral of the values from the inertial sensors, the results obtained show a drift error. The compensation for drift errors is made by comparing the main angular velocity variables related to the estimated data. When the stretch does not show variations in the angular velocities, drift on the estimated data is considered purely. The expected results are the estimates with low root mean squared error (RMSE) about the measured data. At the end of this work, we want to conclude the effectiveness of the method for use in identifying aerodynamic parameters using minimization in the time or the frequency domain of the UAV after flight tests.

Keywords: Estimation, Aerodynamic angles, Flight test, UAV.

1. INTRODUCTION

During the development of manned and unmanned aircraft, knowledge of the aerodynamic model is necessary for some phases of the project. This model is of paramount importance for creating a complete numerical model of the dynamics of the real aircraft under development. Some parameter identification techniques such as the Output Error Method (OEM), presented in Jategaonkar (2006), have as necessary inputs the aircraft's angles of attack and sideslip. These identified models are later commonly used in flight performance simulations, control systems tuning, and stability enhancement systems, (Stevens *et al.*, 2015).

Typically, the angles of attack and sideslip are measured using probe-type instruments with five anemometric sensors (Lie and Gebre-Egziabher, 2013), or pivoted vanes (Rhudy *et al.*, 2013). Anemometric measuring instruments need positioning in the aircraft body, as they cannot be influenced by secondary dynamics originating from the aircraft body and are normally fixed at the ends such as wingtips and nose.

The objective of this research is to use the maneuver reconstruction method presented in Morelli (2010), together with bias adjustments in the final results. The data applied in the methodology were generated through the flight test campaign of the C2 aircraft.

2. THE C2 PLATFORM

The UAV C2 is a new aircraft, the result of the Unmanned Aircraft development project to apply agricultural defensives. The aircraft is designed in its structural architecture with the extensive use of a lightweight and advanced materials, based on Carbon Fiber Reinforced Plastic (CFRP), offering good in-flight performance and structural reliability, (Neves,

2020). Its dimensional properties can be seen in Table 1, as well as the aircraft on the runway during the flight campaign in Figure 1.

Table 1. UAV C2 - Properties.

Properties			
$Wingspan[m]$	$Length[m]$	$Height[m]$	$Weight[kg]$
$5,000$	$2,863$	$1,080$	60

Figure 1. UAV C2 with a vane anemometer on the nose.

3. MANEUVER RECONSTRUCTION METHOD

The maneuver reconstruction method for estimating the angles of attack and sideslip is presented in Morelli (2010), in which the dynamic model's Equation (1) is used for the reconstruction of flight data. However, because there are bias errors in the accelerometers and drift errors in the gyroscopes, after the integral of the values from the inertial sensors, the results obtained show a drift error, (Salyčev, 2004).

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} rv - qw - g\sin(\theta) + \frac{F_x}{m} \\ -ru + pw + g\sin(\phi)\cos(\theta) + \frac{F_y}{m} \\ qu - pv + g\cos(\phi)\cos(\theta) + \frac{F_z}{m} \end{bmatrix} \tag{1}$$

Equation (1) represents the rate of change of aircraft speed in the system fixed to the body of the aircraft, Figure 2. Once the variables of attitude, angular velocities, and accelerations are measured, one can rewrite the Equation (1) into Equation (2), where the accelerations a_x^{CG}, a_y^{CG} and a_z^{CG}, are the accelerations measured in the CG of the aircraft.
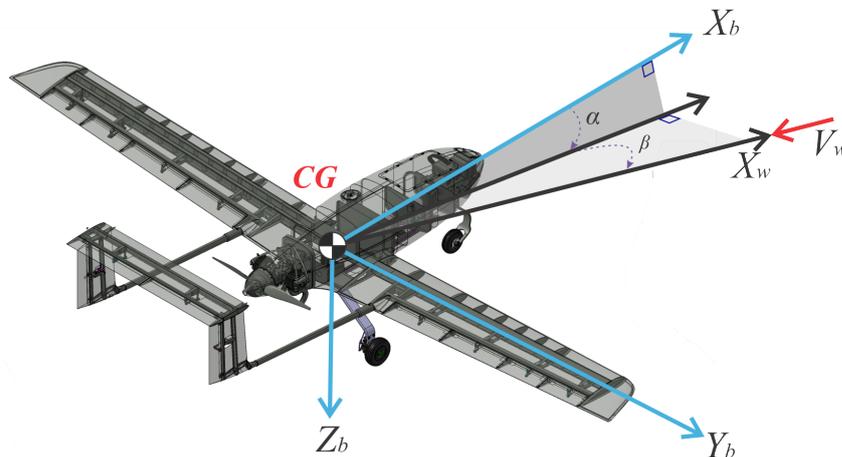

Figure 2. Aerodynamic reference systems, adapted from: Stevens *et al.* (2015)

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} rv - qw - g\sin(\theta) + a_x^{CG} \\ -ru + pw + g\sin(\phi)\cos(\theta) + a_y^{CG} \\ qu - pv + g\cos(\phi)\cos(\theta) + a_z^{CG} \end{bmatrix} \tag{2}$$

According to Stevens *et al.* (2015), the equations that provide the aerodynamic angles α, β and the total speed of the aircraft are governed by the Equations (3), (4) and (5).

$$V_{t,m} = \sqrt{u^2 + v^2 + w^2} \tag{3}$$

$$\beta = \sin^{-1}(v/V_{t,m}) \tag{4}$$

$$\alpha = \tan^{-1}(w/u) \tag{5}$$

Because the tests necessary to obtain the angles of attack and sideslip are carried out during days with little anemometric variation and with the aircraft generally starting in equilibrium conditions, some approximations such as those in the Equation (6), (Morelli, 2010).

$$\begin{aligned} u &\approx V_{t,m} \approx cte \\ \beta &\approx v/V_{t,m} \\ \alpha &\approx w/V_{t,m} \end{aligned} \tag{6}$$

In the present work, it is assumed that airspeed is computed from the dynamic pressure and ambient air conditions (Morelli, 2010), because the aircraft flies at low speed, as described in Equation (7):

$$V_{t,m} = \sqrt{2\bar{q}/\rho} \tag{7}$$

Combining the Equations (2) and (6), we have the approximate equations for small variations of the angles of attack and sideslip around the flight condition, as followed in Equations (8) and (9).

$$\dot{\beta} \approx p\alpha - r + \frac{g}{V_{t,m}}(\cos(\theta)\sin(\phi) + a_y^{CG}) \tag{8}$$

$$\dot{\alpha} \approx q - p\beta + \frac{g}{V_{t,m}}(\cos(\theta)\cos(\phi) + a_z^{CG}) \tag{9}$$

For straight-level equilibrium flight, the approximations of the Equation (10) on the observed states and measurements are adopted.

$$\begin{aligned} \dot{u} &= \dot{v} = \dot{\beta} = \dot{w} = \dot{\alpha} = 0 \\ p &= q = r = 0 \\ v &= \beta = a_y^{CG} = \phi = 0 \\ \theta &= \alpha \end{aligned} \tag{10}$$

With the equilibrium conditions applied in Equation (2), the initial conditions of (α and β) are given by Equations (11) and (12).

$$\beta(0) = 0 \tag{11}$$

$$\alpha(0) = \sin^{-1}(a_{x_0}^{CG}) \tag{12}$$

Consequently, the integral of the Equations (8) and (9), will give rise to the estimates of the angles of attack and sideslip with increasing slip errors over the simulated time due to the input of the real measurements of the inertial sensors in the equations.

4. COMPENSATION OF ANGLES OF ATTACK AND SIDESLIP

4.1 Measurement Compensation

For reading the angles of attack and sideslip, it is necessary to fix sensors far from the aircraft structure, which causes measurement errors, as the coordinate system that governs these angles is centered on the CG of the aircraft, (Stevens *et al.*, 2015). In the reference Klein and Morelli (2006) it is observed a way to shift the sensor measurements, α_m and β_m, to the aircraft CG using the Equations (13) and (14), angular velocities, airspeed and distances of the sensors in relation to the CG, $X_{\alpha_{cg}}$, $Y_{\alpha_{cg}}$, $X_{\beta_{cg}}$ and $Z_{\beta_{cg}}$.

$$\alpha_{cg} = \alpha_m + \frac{qX_{\alpha_{cg}}}{V_T} - \frac{pY_{\alpha_{cg}}}{V_T} \tag{13}$$

$$\beta_{cg} = \beta_m + \frac{rX_{\beta_{cg}}}{V_T} - \frac{pZ_{\beta_{cg}}}{V_T} \tag{14}$$

Similar corrections can be applied for the airspeed measurement, but typically these corrections are minimally divergent from the nominal airspeed values so that these corrections can be waived, (Klein and Morelli, 2006).

4.2 Estimate Drift Compensation

An approach used for drift detection to offset the estimated α and β data is based on the initial flight condition, where the aircraft is in equilibrium. Assuming the Equation 10 the angles of attack and sideslip should be constant under real conditions, (Stevens *et al.*, 2015). Therefore, the drift of the estimates of α and β when the aircraft is in equilibrium can be approximated by the first-degree Equations (15) and (16).

$$\alpha_{e,comp} = \alpha_e - K_{bias,\alpha} time \tag{15}$$

$$\beta_{e,comp} = \beta_e + K_{bias,\beta} time \tag{16}$$

5. RESULTS

The results were obtained through an in-flight campaign in which the aircraft was subjected to longitudinal identification maneuvers as in Santos (2013), during the flights, it was coupled to the inertial data collection system and a pitot-type sensor with two probes for collecting the angles of attack and sideslip. With the data collected by the instrumentation, the measurement corrections mentioned above were applied, because as seen in Figure 1 the anemometric measurement instrument was located in the nose of the UAV, the corrected measurement data was defined as measured data α_m and β_m. In Table 2 it is possible to observe all the data used in the estimate.

Table 2. Data for estimating anemometric angles

Data	Sensor reading
p	Gyrometers
q	
r	
a_x^{CG}	Accelerometers
a_y^{CG}	
a_z^{CG}	
$V_{t,m}$	Anemometric sensor
ϕ	Sensory fusion resulting from the system
θ	
ψ	

Applying the maneuver reconstruction methodology to estimate α and β, the preliminary estimated variables α_e and β_e were obtained as results of the integral of Equations (8) and (9) using the fourth-order Runge-Kutta method. Likewise,
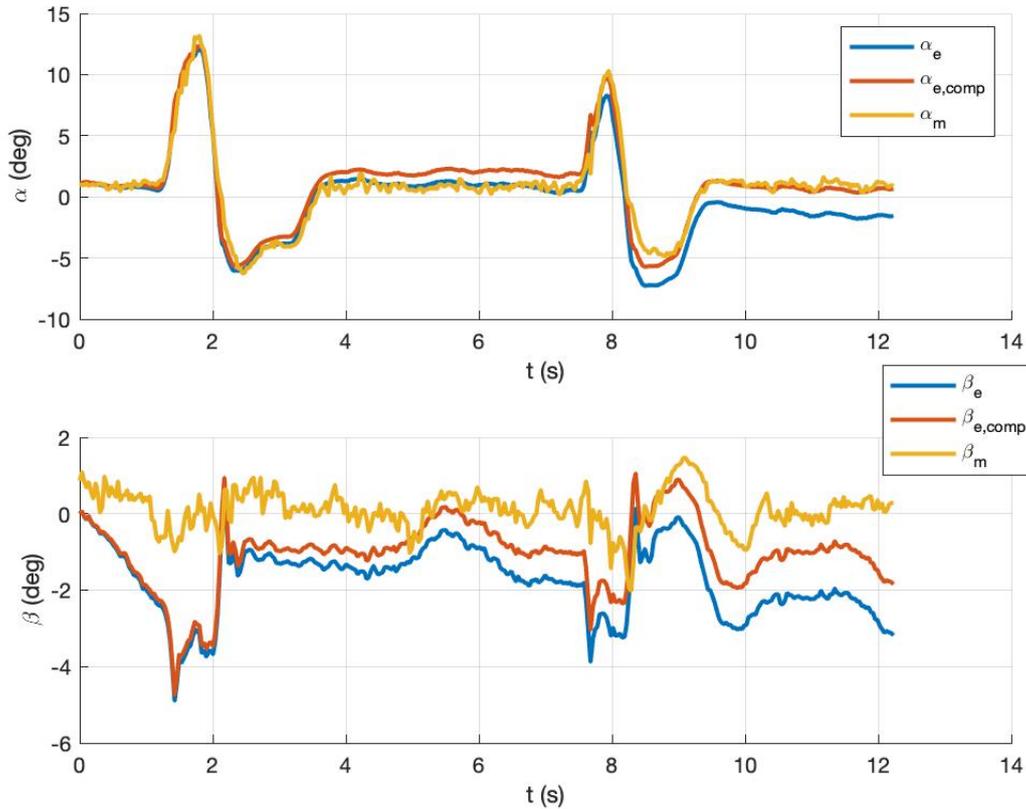
Figure 3. α and β estimated, estimated offset and measured

using the drift correction on the estimated values, the estimated variables $\alpha_{e,comp}$ and $\beta_{e,comp}$ were obtained, resulting from the subtraction of the bias effects of the preliminary estimates. An excerpt taken from a flight test with two doublet elevator maneuvers can be seen in Figure 3.

For evaluating the results shown in Figure 3, the root mean squared error (RMSE) was adopted between the estimated values and the measured values adopted as a reference of α and β.

Table 3. Root Mean Squared Error (RMSE)

Data	RMSE(%)
RMSE α_e	1.9744
RMSE $\alpha_{e,comp}$	1.2739
RMSE β_e	18.3678
RMSE $\beta_{e,comp}$	12.9583

6. CONCLUSION

With the research, it was possible to conclude that the maneuver reconstruction methodology is feasible for application in the identification of aerodynamic parameters in rigid aircraft as long as the balance considerations are followed during the in-flight test. For the studied case of the longitudinal maneuvers performed to identify the longitudinal parameters, the $\alpha_{e,comp}$ obtained an error close to 1%, according to Table 3 which makes the implementation viable for identification both in the domain of time and in the domain of frequency.

Despite the drift compensation from the inertial sensor measurements, the result of the angle $\beta_{e,comp}$ obtained an error of approximately 13%, such error can be related to the disturbances of lateral winds during the test day in flight in conjunction with non-alignment of the roll angle $\phi = 0$ during the longitudinal maneuver. However, despite this error being relatively high during the longitudinal identification, the identified model does not include the lateral-directional states of the aircraft, which makes it possible for the longitudinal identification.

For a better approximation of the estimated values with the reference values, it is desired to implement a cascade Kalman filter for the iterative filtering of inertial data together with the anemometric data taking into account a previous model calculated from the aircraft using computational fluid dynamics (CFD) methods.

Based on this iterative estimation, it is also desired to carry out real-time estimation tests onboard the aircraft to verify the feasibility of implementing control laws using data estimated on board.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE