IDENTIFICATION OF THE LATERAL-DIRECTIONAL MODEL OF THE VECTOR-P, UNMANNED AERIAL VEHICLE

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Abstract

The present work describes the system identification process of the lateral-directional stability derivatives of an Unmanned Aerial System (UAS) [1]. The Maneuver, Model, Method, Measures and Validation (M4V) [2] , is a well known in-flight identification methodology that was applied to the VECTOR-P UAS. The maneuvers adopted to excite the lateral modes of the system were evaluated with the energy spectral density (ESD). The data was acquired during flight tests by the data acquisition system specifically developed to the Vector-P. Finally, the validation of the identified parameters was performed using statistical methods.

1 Introduction

The fast growing of UAS applications in the last years is requiring the use of advanced engineering tools to project them and to guarantee a safe operation. Additionally, the facility to obtain an UAS and the advances in small on-board electronics allows to test theories and methods in practice, what before was possible only with manned aircraft or large and expensive equipments.

UAS also can be used as a test bed for new flight control systems. Their relatively low cost makes them a low risk test platforms. There has been an increase in the number of works dealing with in-flight system identification for UAS. This growing number of studies is due to the expanding variety of tasks for UAS [3].

The Vector-P aircraft is shown in Fig.1. It is an UAS manufactured by Intellitech Microsystems from USA and his payload is adequate to install a suitable data acquisition system. His configuration has a pusher engine, wich is suitable for less vibration interference in the sensors installed in the front of the aircraft. The system has a fixed wing, made of composite material and is operated in the Aeronautical System Lab (LSA) at the Aeronautical Institute of Technology (ITA-Brazil). This platform has been used for many studies, as evaluation of different devices for in-flight data acquisition and for evaluation of different system identification methods [4].

Fig. 1 Vector-P

The first identification study on the Vector-P at ITA, was done by Santos [5] and was focused only at the longitudinal motion aerodynamic derivatives. The present paper discusses the system identification process applied to the lateral-directional aerodynamic stability derivatives.

The system identification methodology provides a mature way to build a mathematical model with acceptable precision. The methodology used is known as M4V (Maneuver, Model, Method, Measures and Validation), as described by Jategaonkar [2].

2 Literature Review

The use of system identification based on Jategaonkar [2] has need successfully applied to UAS, as for example [3]. The work [3] identified the parameters of a model using real flight data and subsequently validated and verified the identified model.

Another example of use of system identification to UAS is [6]. Quadrotors UAS are attracting great interest and finding new applications in both civil and military fields. The design of reliable control systems for these devices requires a precise dynamic model. The system identification methodology can provide a safe and accurate way to develop different dynamic models and test these models with more advanced controllers [6].

Other relevant application with great current demand is the use of system identification to characterize the servoaeroelastic characteristics of a flexible aircraft. Lightweight and flexible wings can achieve fuel efficiency due to reduced drag, consequently increase the aircraft range. A flexible structure can deform and affect the coupled unsteady aerodynamics in Flight. This could make the aerodynamic analysis very difficult requiring more effort on in-flight test and validation. As an example the study of ref [7] focused the identification of a small flexible aircraft using specific excitation to obtain the dynamic modes of interest.

3 Theoretical Background

The methodology of identification described by the "M4V" is presented in Fig. 2, where the main steps are maneuver, measure, method, model and validation.

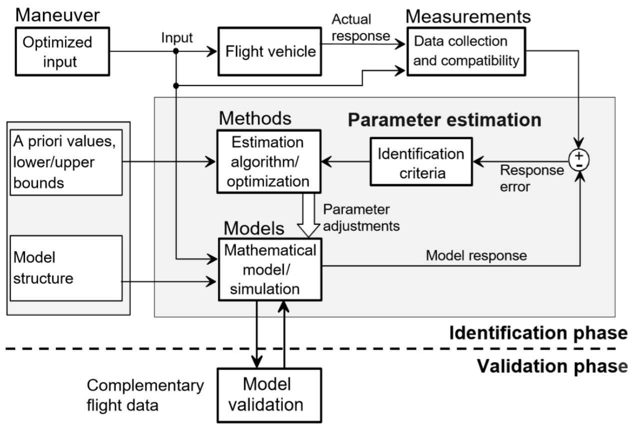

Fig. 2 M4V basic of flight vehicle system identification [2]

Hereafter, each one of the main topics is discussed focusing the application on the Vector-P investigation.

3.1 Maneuver

The basic dynamics modes of motion associated to the lateral directional movement are rolling motion, dutch-roll and spiral mode. In this identification studies, only two modes of flight were excited, the rolling motion and the dutch-roll. Due to difficult to accomplish the spiral maneuver, this maneuver was not excited.

The ideal maneuvers to extract the dutch roll mode are multistep 3-2-1-1 and doublet, applied to the rudder. To specify these maneuvers we have applied the energy spectrum as suggested by Jategaonkar [2] to tune the natural frequency of each respective flight mode, as shown in Fig.3.

The time duration of each of the pulses of the maneuver is calculated by equation 1, for the doublet input and by equation 2, for the multistep 3-2-1-1 [2].

$$\Delta t_{DBLT} = 2.3/\omega_n \tag{1}$$

$$\Delta t_{3211} = 2.1/\omega_n \tag{2}$$

To excite the rolling motion mode is recommended to apply the bank-to-bank maneuver, which consists in the application of an input to

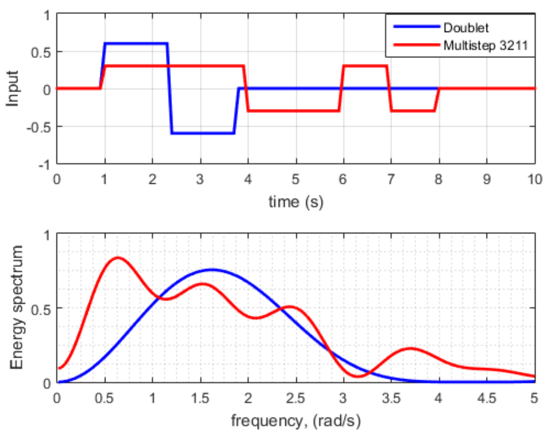

Fig. 3 Time and frequency domain specification of standard inputs for lateral directional system identification

the ailerons and observe the resulting rolling angle (ϕ). The recommended range of the rolling angle is $\pm 10^{o}$ e $\pm 60^{o}$ [2]

3.2 Measurements

To perform the identification of the lateral directional model, it is necessary to acquire flight data with a specific instrumentation. It is also necessary to know the geometrical and inertial properties of the aircraft, such as mass (m), wing area (S), span (b), matrix of inertia moments (I) and the position of the sensors relative to aircraft center of gravity.

The data collected include the Euler angles, the angle of attack and slide-sleep, drift angle and the true aircraft airspeed during the Flight test.

3.3 Methods

The method of identification applied was the Output Error Method (OEM), shown in Fig. 4. This method consists to minimize the cost function (J) associated with mean square error between the measured data and the simulated data using the current aircraft parameters and aerodynamic derivatives, see equation(3). The cost function is dependent on the noise covariance matrix (R) and of the vector of aerodynamic parameters to be identified (Θ). The data used to calculate the cost function include the vector of data obtained during flight test (z) and the vector of data estimated by the model (y), the difference between these data generates the error vector at each sample time. Na optimization algorithm is used to minimize the mean square error in an iterative fashion, until the optimization algorithm stops at a given criterion, and me could stated that the optimization system converged to a set of suboptimal parameters.[2]

$$J(\Theta,R) = \frac{1}{2}\sum_{k=1}^{N}[z(t_k)-y(t_k)]^T R^{-1} [z(t_k)-y(t_k)] + \frac{N}{2}[det(R)] + \frac{Nn_y}{2}ln(2\pi) \tag{3}$$

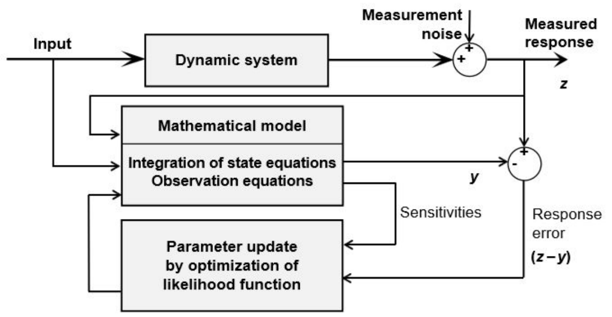

Fig. 4 Block schematic of Output Error Method [2]

The identification algorithm was implemented in Matlab.

3.4 Model

The dynamics model of the aircraft is obtained by defining the body coordinate system of the Vector-P according to Fig. 5.

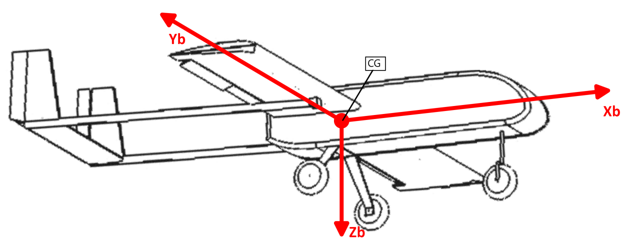

Fig. 5 Body reference system for the Vector-P UAS.

The state-space equations of non-linear dynamics model for the lateral directional dynamics of a fixed wing aircraft is given by [8]:

$$\dot{v} = -ru + pw + gsin(\phi)cos(\theta) + \frac{F_y}{m} \quad (4)$$

$$\dot{\phi} = p + qsin(\phi)tan(\theta) + rcos(\phi)tan(\theta) \quad (5)$$

$$\dot{p} = (c_1 r + c_2 p)q + c_3 L + c_4 N \quad (6)$$

$$\dot{r} = (c_5 p + c_2 r)q + c_4 L + c_6 N \quad (7)$$

The variables u, v and w represent the velocities in directions (X_b, Y_b, Z_b) respectively, m is the mass of the aircraft, (p,q,r) are the angular rates measured around the reference axis of the body system. The Euler angles ϕ and θ are respectively the roll angle and pitch angle. The parameters c_1 to c_6 are associated to the moments of inertia of the aircraft, and the specification of these parameters are described in Fischer [9].

The variable F_y is the lateral force applied in direction Y_b and is associated to dynamic pressure $(\bar{q})$ and wing area (S). L *and* N are the angular moments generated around the axis X_b and Z_b respectively, and are referenced to $\bar{q}$, S and the span b. The equations mentioned above are represented below.

$$F_Y = C_Y \bar{q} S \quad (8)$$

$$L = C_l \bar{q} S b \quad (9)$$

$$N = C_n \bar{q} S b \quad (10)$$

The coefficients C_Y, C_l and C_n, represent the lateral force coefficient, the rolling aerodynamic coefficient and the pitch aerodynamic coefficient, respectively. They are calculated by the following equations.

$$C_Y = C_{y\beta}\beta + C_{y\delta_a}\delta_a + C_{y\delta_r}\delta_r + (C_{yp}p + C_{yr}r)\frac{b}{V_t} \quad (11)$$

$$C_l = C_{l\beta}\beta + C_{l\delta_a}\delta_a + C_{l\delta_r}\delta_r + (C_{lp}p + C_{lr}r)\frac{b}{V_t} \quad (12)$$

$$C_n = C_{n\beta}\beta + C_{n\delta_a}\delta_a + C_{n\delta_r}\delta_r + (C_{np}p + C_{nr}r)\frac{b}{V_t} \quad (13)$$

The values of δ_r and δ_a are the inputs applied to the rudder and to the ailerons. V_t is the true airspeed.

The equation bellow prescribes the aerodynamic parameters to estimated by the system identification process. They integrate the parameter vector, Θ.

$$\Theta_{par} = [C_{y\beta}C_{y\delta_a}C_{y\delta_r}C_{yp}C_{yr}C_{l\beta}C_{l\delta_a} C_{l\delta_r}C_{lp}C_{lr}C_{n\beta}C_{n\delta_a}C_{n\delta_r}C_{np}C_{nr}] \quad (14)$$

These parameters, are known as the stability derivatives of the aircraft for the lateral directional dynamic. In this study we consider the linearized equations of motion, when the movement is restricted to small perturbations around the equilibrium flight of the aircraft.

The state-space x is given by:

$$x = \begin{bmatrix} v & \phi & p & r \end{bmatrix} \quad (15)$$

The output vector y and input vector u as are described bellow,

$$y = \begin{bmatrix} a_y & \beta & \phi & p & r \end{bmatrix} \quad (16)$$

$$u = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix} \quad (17)$$

3.5 Validation

In the process of validation it was verified the plausibility of the identified parameters for the proposed model.

Another method used to validation is the analyses of parameter error covariance matrix given by P.

$$P \approx \left\{ \sum_{k=1}^{N} \left[\frac{\partial_y(t_k)}{\partial\Theta} \right]^T R^{-1} \left[\frac{\partial_y(t_k)}{\partial\Theta} \right] \right\}^{-1} \quad (18)$$

The elements of main diagonal of P represents the standard deviation of the estimation of the parameters and is bounded by the limits of Cramer-Rao (CR) [10]. Where t_k is the time points at each sampled measurement.

$$CR = \sigma_{\theta_i} = \sqrt{p_{ii}} \quad (19)$$

Here p_{ii} are the elements of main diagonal of P and the CR values should be lower then 20%, to have an acceptable accuracy [11].

For the residual analysis it was applied the method of Goodness of Fit, calculated by the following equation [2]:

$$\sigma_i = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[z_i(t_k) - y_i(t_k)]^2}, \quad i = 1, 2, \ldots, n_y \tag{20}$$

It was also evaluated the correlation between the measured data and the estimated data, calculated with a normalized function of the crossed covariance given by ρ_{zy}, as presented in [12]. The desired value for this parameter should be greater than 70%.

4 Methodology

In this section is presented the experimental results of the M4V methodology.

Initially it was analyzed the applied maneuvers used during flight tests to collect flight data. For the dutch roll mode it was observed that the natural frequency of the pole is 4.6 rad/s, and the best selected maneuvers for the parameters identification are presented in Fig.6, a more details study of the presented maneuvers was developed in [9].

The maneuvers were performed manually by the UAS pilot. Due to the difficulty performing this kind of maneuver, the inputs were distorted.

The maneuvers applied to excite the rolling motion are presented in the Fig. 7

Following the steps of the discussed methodology, it was implemented a data aquisition system to collect the flight data, as developed at the Aeronautical Systems Laboratory (LSA).[13], [14]

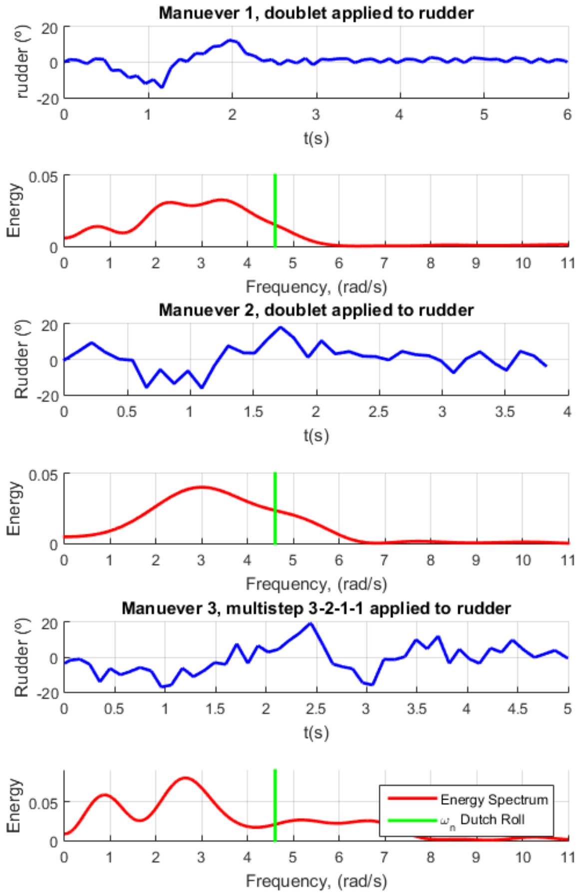

Fig. 6 Maneuvers used by identification applied for Dutch roll

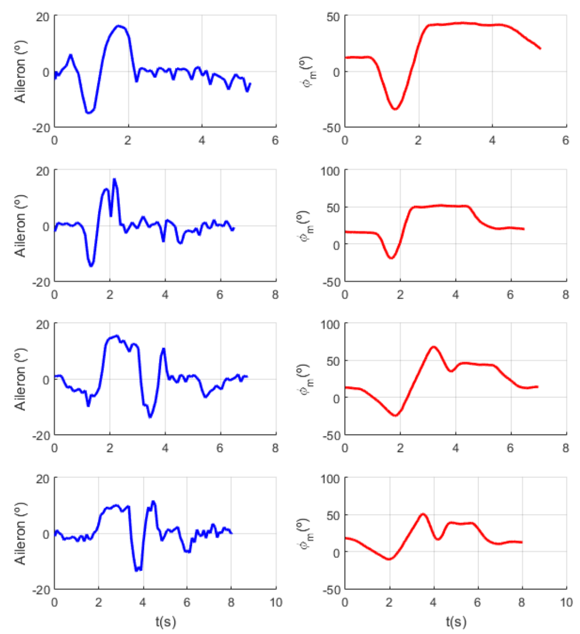

Fig. 7 Maneuvers used by identification applied for roll

The installed instrumentation system, was a CompactRIO (cRIO) board, cRIO-9014, by National Instruments, which has a SD card memory module to record the flight data, a slot to read analogic data and a slot to read digital data, including cards to serial communication RS-232. The hardware installed is presented in Fig.8. The program for data acquisition was developed in Labview.

Fig. 8 cRIO-9014

The measurements of side-slip angle (β) and airspeed was made with a five hole probe and anemometric system, called Smart Air Data Boom, as shown in Fig. 9.

Fig. 9 Smart Air Data Boom

To measure the attitude of the aircraft, as given by the Euler angles, ϕ and θ, the lateral acceleration and rate angles, it was used an inertial unit Crossbow AHRS-400CC-200, as shown in Fig.10

Fig. 10 Crossbow, AHRS-400CC-200

The deflection of the control surfaces, aileron and rudder was collected by the signals from the servomotor potentiometer, attached to the respective control surface. This instrumentation was done developed by Franco, 2009[14].

The specification of Vector-P is as presented in Table(1).

Table 1 Parameters of the Vector-P

Variable	simbol	valor
Mass	m	31.5 kg
Wing area	S	1.15m²
Span	b	2.58m
Inertia	I_{xx}	3.14 kg m²
Inertia	I_{yy}	8.25 kg m²
Inertia	I_{zz}	10.40 kg m²
Inertia	I_{xz}	0.01 kg m²

For the validation of the identified aerodynamic model, two maneuvers in sequence were used, one applied to aileron and the other to rudder. These maneuvers were not used to the parameter identification studies and are presented in Fig.11

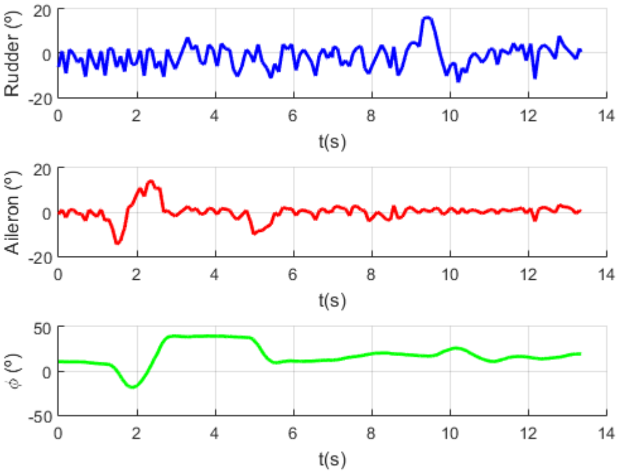

Fig. 11 Input applied at Rudder and at Aileron, and angle ϕ

The stopping criterion adopted for the identification studies were a maximum of 50 iteration or the mean of the residual variation equal to:

$$(det(R)_{i-1} - det(R)_i) / det(R)_i \leq 1e^{-11} \quad (21)$$

After the implementation of the identification algorithm, following results were obtained.

5 Results

The evaluation of the in-flight results was done in three phases, including the validation of the maneuvers used in the Flight test, verification of the compatibility of the derivatives obtained by the system identification method and the capacity of extrapolation of the model to validate Flight data measured but not used in the identification studies.

5.1 Check of the Maneuvers

The maneuvers used for identification of lateral directional derivates were bank-to-bank roll, doublet and multistep 3-2-1-1 for dutch roll. After many attempts of identification, it was observed that the best results were obtained alternating the maneuvers. Different ways of identification have been tried. First the identification of each maneuver was done independently, then the arithmetic mean was calculate between the results of each segment of the maneuvers. Next, the identification was applied for each mode. The best result was achieved with the concatenation of different maneuvers as shown in Fig. 12.

Care was taken during the concatenation process of the maneuvers, the aircraft should be in the same stabilized condition at the end of each maneuver and at the beginning of the next. This avoids abrupt variations in the parameters, even if the maneuvers have not been executed in the sequence during the flight tests.

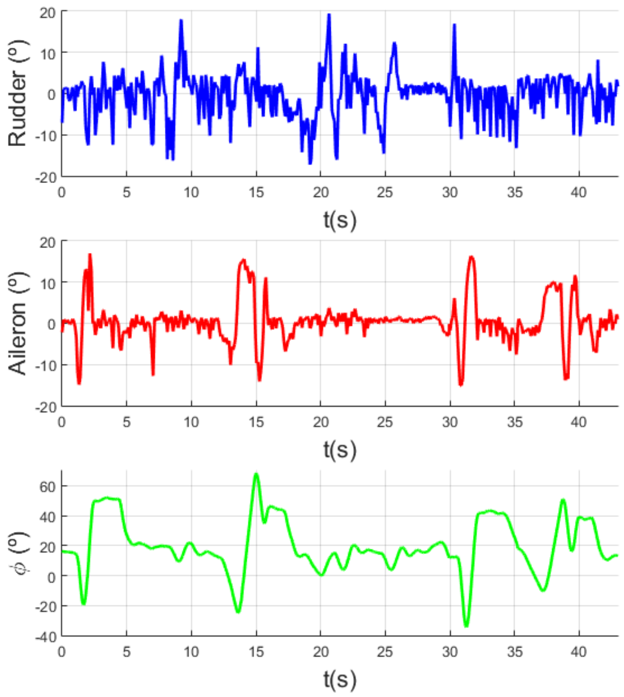

Fig. 12 Input applied at Rudder and at Aileron, and angle ϕ

5.2 Results of the identification process

For the identification using the OEM method was necessary to estimate the initial conditions for the parameter vector. This initial values were obtained by Vortex Lattice method [15].

The system reached the convergence requirement in the 42nd iteration. In the Fig.13, is presented the system output, comparing the measured data with and the estimated data.

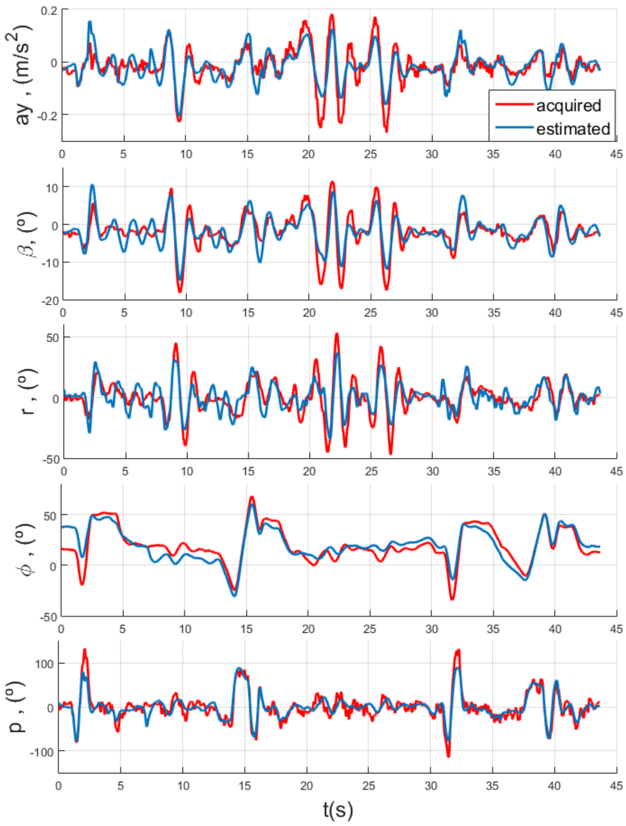

Fig. 13 Result of the identification process

The evolution of the minimization process of the cost function can be seen in Fig.14.

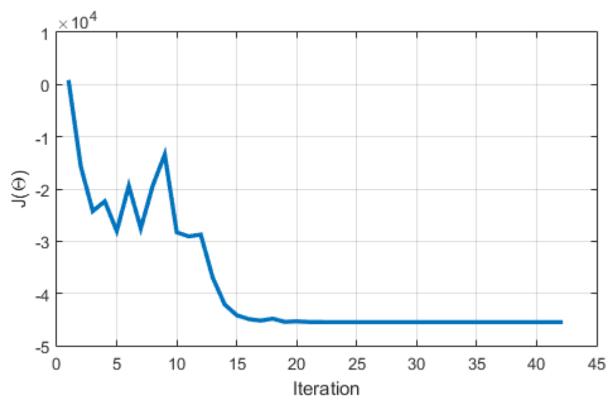

Fig. 14 Cost function

The estimated values for the parameters are as presented in Table(2).

5.3 Results of the Validation

The last step of this work was to validate the identified parameters. The result obtained is shown in Fig.15, one can observe that the estimated values and the value of data acquired are very similar, showing the capability of the model to explain the maneuvers not used in the identification process.

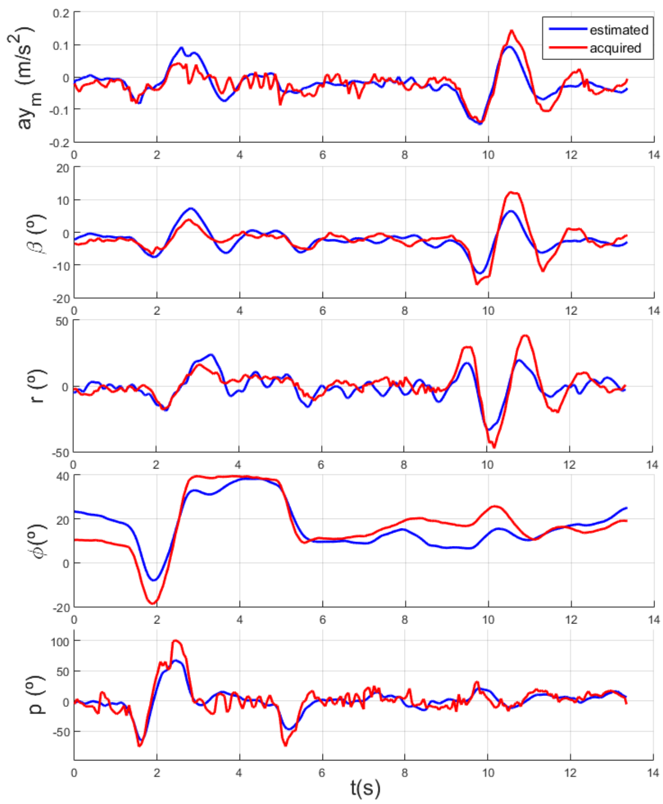

Fig. 15 Result of the validation process

It the validation process it was also applied the CR criterion and the highest value calculated was 10.79%, as presented in Table(2). This value is less than 20%, which meets the expected precision.

The result of the Goodness of Fit validation is shown in Table(3). It is observed that the residual values are very low, indicating the results can represent the identified system.

In Table(4) it can be seen the correlation coefficients computed with the validation criterion, and as expected, values greater than 70% were obtained. The lowest value observed was 82%.

Table 2 Identified parameters and CR

Parameter	Value	CR
$C_{y\beta}$	0.0290	2.85%
$C_{y\delta_a}$	0.0176	3.13%
$C_{y\delta_r}$	-0.0082	3.13%
C_{yp}	-0.0243	5.42%
C_{y5}	0.0202	7.73%
$C_{l\beta}$	-0.0285	5.49%
$C_{l\delta_a}$	0.0666	3.17%
$C_{l\delta_r}$	-0.0113	7.17%
C_{lp}	-0.1317	3.79%
C_{l5}	0.0490	9.17%
$C_{n\beta}$	0.0900	1.79%
$C_{n\delta_a}$	0.0224	10.79%
$C_{n\delta_r}$	0.0425	3.08%
C_{np}	-0.0772	6.91%
C_{nr}	-0.1627	3.34%

Table 3 Uncertainties

Parameter	Value	unit
a_y	0.002	m/s²
ϕ	0.690	degrees
β	0.066	degrees
p	0.799	degrees/s
r	1.230	degrees/s

Table 4 Uncertainties

Parameter	Value
a_y	84%
ϕ	82%
β	84%
p	90%
r	83%

6 Conclusions

The process of identification can contribute to the improvements of the Flight quality of the UAS models. The difficulties of parameter identification process are mainly the aircraft instrumentation and the flight test operation to collect the data.

Therefore, it can be concluded that despite the difficulty to define the sequence of maneuvers, the best way to get accurate results is to mix between different maneuvers for each mode to be identified. Also, it is important to concatenate the maneuvers at the same stabilized point, to get a good identification result.

Another observation is that the maneuvers executed are performed by the pilot, and this causes a variation in the execution times of the maneuver, causing a displacement of the peak of energy in the frequency domain. To improve, these maneuvers must be programmed in the on-board computer in an automatic fashion. Despite these drawbacks, the obtained results were satisfactory and can be applied to obtain the model of an UAS.

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