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SYSTEM IDENTIFICATION BASED ON FLIGHT TEST DATA AND AUTOPILOT DESIGN FOR LONGITUDINAL MOTION OF THE VECTOR-P UAV

Jônatas Sant'Anna Santos
Luiz Carlos Sandoval Góes
Instituto Tecnológico de Aeronáutica, Praça Marechal Eduardo Gomes, 50, Vila das Acácias, 12228-900, São José dos Campos, SP, Brazil.
jsantos@ita.br, goes@ita.br

Abstract. *This paper presents a system identification based on flight test data of the Vector-P Unmanned Aerial Vehicle which perform the parameters estimation and model validation. The flight data is used to estimate the longitudinal aerodynamic coefficients. The system identification program is based on the output error method. Heuristic method based on a stochastic search is applied to improve global convergence. The Vector-P theoretical model with aerodynamic parameters estimated by software based on the Vortex Lattice Method is used to determine the desired frequencies in which the short period and phugoid mode is featured. Optimal time step for excitation is design to provide the bandwidth of power spectral density that contains the desired frequencies. A multistep 3-2-1-1 and doublet input are applied on elevator aiming to excite the longitudinal motion. The data acquisition system composed by computer board and GPS, pressure and inertial sensor is employed. In order to perform the model validation, the Goodness of Fit criteria is applied to verify the deviation between the computational and actual results. An altitude-hold autopilot is designed using the identified model and, finely, it is shown a comparison between the dynamics behavior.*

Keywords: *UAV, Flight Test Data, System Identification, Autopilot, Output Error Method, Model Validation*

1. INTRODUCTION

It has been explored the development of UAVs since the Second World War. The improvement of embedded systems has been a worldwide concern. The higher the technology, UAVs will perform more functions and his reliability will be also higher.

UAVs are essentially aircraft without a human pilot inside. The weight of this vehicles can range from a few grams to 12 tons having 35 meters of wingspan, as presented by (d'Oliveira, 2005). There are many types of UAVs around the world. There are some companies, organizations and universities that are conducting activities in the UAV area in Brazil: Instituto Tecnológico de Aeronáutica (ITA), Projeto VANT (DCTA), Army Technology Center (CTEx) Navy Research Institute (IPqM), AVIBRAS, ATECH, Flight Technologies, XMobots, AGX Technology, Santos Lab, Renato Archer Research Center (CENPRA), University of São Paulo (USP) - São Carlos, Foundation for Technological Innovations (FITec), Centre for Studies and Systems of Recife (CESAR) and Gyrofly Innovations.

The Ministry of Defense mentioned that the national development of UAVs is justified by its strategic importance to national autonomy and can be one of the first programs of the effective integration of science and technology sectors (d'Oliveira, 2004).

This paper contributes to UAVs research area, aiming to present the dynamic system identification of Vector-P UAV with flight test data and perform an autopilot design, using the identified model. In order to perform the aircraft aerodynamic coefficients identification, it was used the parameter estimation method called Output Error Method, which consists in minimizing the output mean squared error of the actual plant and the identified model output. The minimization of the cost function was performed by the combination of the Levenberg-Marquardt method with a heuristic method based on stochastic search. The maneuvers performed during the flight test campaign were a "multistep 3-2-1-1" and "doublet" aiming to excite the aircraft dynamic modes in the interested frequency. An embedded data acquisition system was implemented to get the information from flight test associated with the aircraft longitudinal motion. The identified model validation was performed through the criteria Cramér-Rao bonds and Goodness of Fit. In the study of autopilots, the modern control technique based on Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) was used to design the gains of the control loops.

2. THE VECTOR-P UAV

The Vector-P is an Unmanned Aerial Vehicle manufactured by Intellitech Microsystems from USA. The UAV was designed by aerospace engineers, who made it entirely of composite material and it presents a relatively common configuration for vehicles of the same size, with an almost square fuselage, wing flaps with no dihedral, two vertical stabilizers, horizontal tail and a tail boom, as shown in Fig. 1.

Figure 1. Flight campaign with the Vector-P UAV

According to Borges (2008), the Vector-P was purchased by the Aeronautical and Mechanical Engineering Department at ITA to be used as a testbed for academic purposes.

3. SYSTEM IDENTIFICATION

In order to identify the parameters of an aircraft dynamic system it is necessary to measure some inputs and outputs signals. In this paper the data-gathering were taken from flight test campaign. The dynamic equations selected in the identification system program must provide appropriated approximation for the plant behavior.

The inputs of the system identification program developed in this research, that is based on Klussendorf (2008) program, are mathematical model analysis, time step for maneuvers, known parameters, unknown parameters to be estimated, initial parameters, constraints parameters and methods to minimize the cost function value.

Starting the identification procedure, five maneuvers were chosen during the flight campaigns. Two doublet and two multistep 3-2-1-1 maneuvers were selected to parameter estimation process and another doublet maneuver to the model validation. The power spectral densities of each maneuver were analyzed. The theoretical model obtained in the laboratory was used to obtain the frequency values that were expected in the response of the system.

The parametric model, known parameters and parametric constrains were determined, a cost function was chosen and methods for global and local convergence was set. The system identification program was used to estimate the coefficients in each identification process. After that, the average values of the estimated parameters was obtained. The model validation was performed by comparing its response to the measurement data of the plant.

The first validation criterion applied was to analyze the cost function value. The deviation for each parameter is calculated. A noise analysis is done by calculating the deviation which is the error of each output.

The longitudinal motion of rigid-body and fixed-wing aircraft can be represented by Eq. (1) to Eq. (5).

$$\dot{q} = c_5\, p\, r - c_6(p^2 - r^2) + c_7 M \tag{1}$$

$$\dot{\theta} = q\, cos\phi - r\, sin\phi \tag{2}$$

$$\dot{u} = r\, v - q\, w - g\, sin\theta + \frac{F_x}{m} \tag{3}$$

$$\dot{w} = q\, u - p\, v + g\, cos\phi cos\theta + \frac{F_z}{m} \tag{4}$$

$$\dot{H} = u\, sin\theta - v\, sin\phi cos\theta - w\, cos\phi\, cos\theta \tag{5}$$

where m is the aircraft mass, F_x and F_z are the aerodynamic resultant force components, M is the moment associated to the rotation axis y of the aircraft and c_5, c_6 and c_7 are constants values obtained by inertia.

The unknown parameters in the force and moment equations are the aerodynamic coefficients C_L, C_D and C_m showed in the Eq. (6), Eq. (7) and Eq. (8).

$$C_L = C_{L0} + C_{L\alpha}\alpha + C_{L\delta el}\delta p + C_{Lq} q \frac{\bar{c}}{V} \tag{6}$$

$$C_D = C_{D0} + \frac{{C_L}^2}{\pi A R e} \tag{7}$$

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$$C_m = C_{m0} + C_{m\alpha}\alpha + C_{m\delta el}\delta p + (C_{mq}q + C_{m\alpha}\dot{\alpha})\frac{\overline{c}}{V} \tag{8}$$

where the differential pressure control variable is called by elevator deflection. The identified parameters are described in the Eq. (6) to Eq. (8). The parameters vector to be identified are shown in the Eq. (9).

$$\theta = [C_{L0}\ C_{L\alpha}\ C_{Lq}\ C_{L\delta e}\ C_{D0}\ C_{m0}\ C_{m\alpha}\ C_{mq}\ C_{m\dot{\alpha}}\ C_{m\delta e}]^T \tag{9}$$

The output **y**, state **x** and control **u** vectors are described by Eq. (10), Eq. (11) and Eq. (12).

$$\mathbf{y} = [V_t\ \theta\ q\ \alpha\ H]^T \tag{10}$$

$$\mathbf{x} = [u\ w\ \theta\ q\ H]^T \tag{11}$$

$$\mathbf{u} = [\delta p\ \pi]^T \tag{12}$$

The system identification program is composed by a heuristic search algorithm to improve the global convergence and the Levenberg-Marquardt algorithm for local convergence. The cost function to be minimized it can be only the determinant of the Covariance matrix R showed in Eq. (13), as discussed by Jategaonkar (2006).

$$J(\theta) = \mid \mathbf{R} \mid \tag{13}$$

The heuristic search algorithm used in this paper selects 11 points randomly at which the values of the cost function will be calculated. The point that has the lowest cost value is selected and the process is repeated. This process can be done as often as necessary. Finally, in the last point selected it is applied a search algorithm for local minimum convergence.

In order to generate the theoretical model, it was used data from simulation in the laboratory, in which the parameters were identified by the TornadoÂő software, as displayed in Tab. 1. This software is based on the Vortex Lattice Method.

Table 1. Parameters identified by the Tornado® software

C_{L0}	$C_{L\alpha}$	C_{Lq}	$C_{L\delta e}$	C_{D0}	C_{m0}	$C_{m\alpha}$	C_{mq}	$C_{m\delta e}$
0.311	5.154	9.417	0.419	0.005	-0.146	-2.122	-16.286	-1.39

After linearize the dynamic equations using an equilibrium condition and the theoretical values parameters, it is possible to conclude that the desired poles frequencies is approximately equal to 10.3 rad/s or 1.64 Hz for the short period motion and 0.406 rad/s or 0.065 Hz for phugoid motion. Therefore, the optimal time intervals that will excite the system in the desired frequencies based on the theoretical model are $\Delta\ t_{DBLT}$ = 0.223 s and $\Delta\ t_{3211}$ = 0.49 s.

The optimal time step and frequencies calculated from the theoretical model were used as reference set and to compare results.

4. AUTOPILOT DESIGN

The control system is a fundamental part for autonomous UAVs because the aircraft does not have any human pilot inside. Or the system is totally dependent on autopilot that has implemented functions to reach the mission objective, or it has a wireless communication allowing to control the aircraft by a human pilot on the ground station. There is a hybrid solution when it can set to control the aircraft using an autopilot or a human pilot by wireless communication.

This paper is focused in the autopilot solution. The architecture proposed by Stevens and Lewis (2003) for altitude-hold autopilot is shown in the Fig. 2, which shows the control loop for the altitude tracking. The inner loop of this architecture is called by Stability Augmentation System (SAS).

The gains in the control loop were designed to perform a closed loop dynamic simulation, which means that the SAS and altitude-hold autopilot was implemented and it was used identified model. This architecture is selected and the gains were designed modern control technique based on Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT). A simulation was performed by setting the initial conditions equal to equilibrium condition of longitudinal motion and using a wind shear disturbance. Finally, a comparison between the dynamic response of the open loop and closed loop was made.

5. SYSTEM IDENTIFICATION RESULTS

Four inputs were selected for the identification processes consisting in two doublets and two multistep 3-2-1-1 inputs, as shown in Fig. 3. This figure also shows the elevator variation started from the equilibrium condition.

It is important to analyze how fitted are the computed data and the flight test data in the Fig. 4 and Fig 5, aiming to indicate that the models obtained by the vectors of estimated aerodynamic coefficients represent the dynamic model. It can be analyzed by the cost functions values.

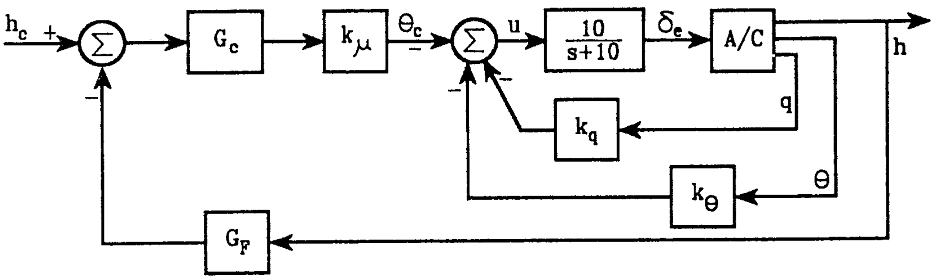

Figure 2. Altitude-hold autopilot architecture

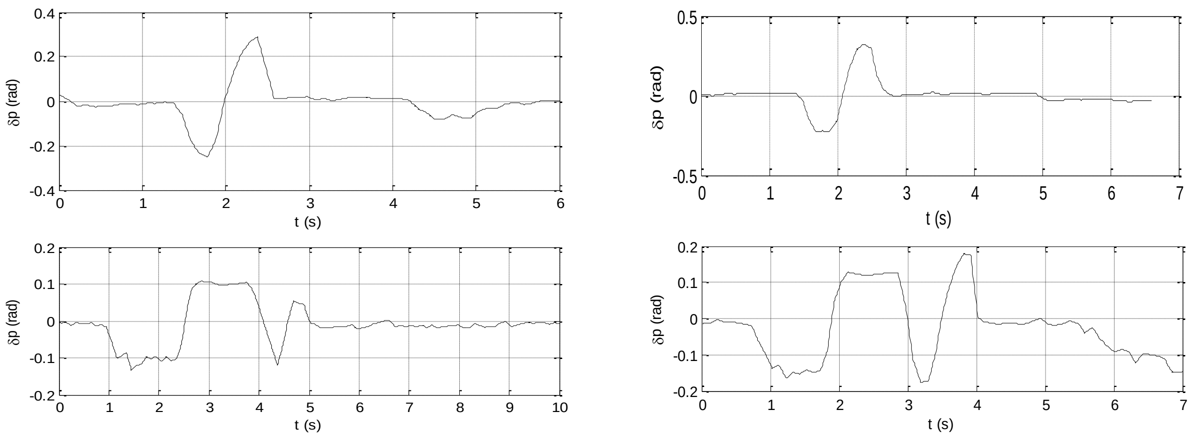

Figure 3. Time history of the input signal: Doublet and multistep 3-2-1-1 maneuvers

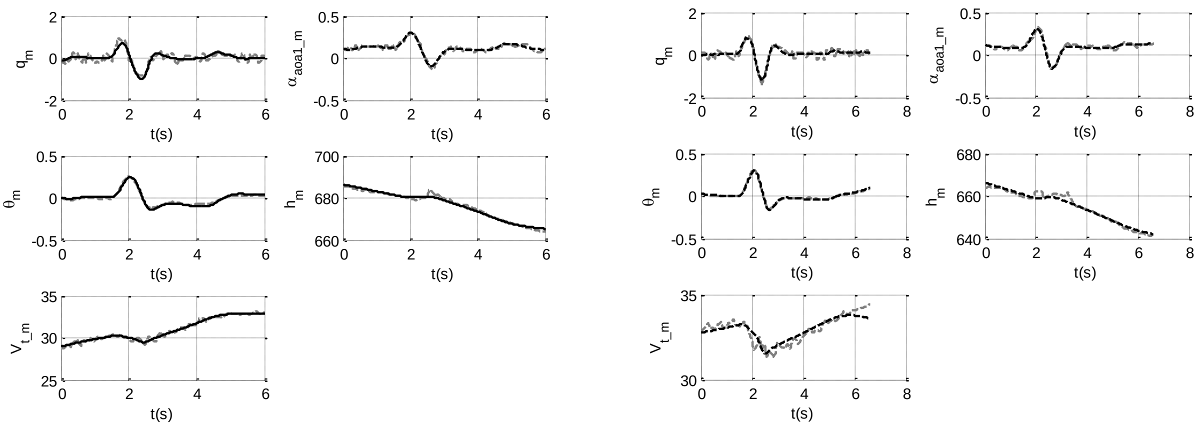

Figure 4. Comparison between flight test data and computed responses containing the estimated parameters and a doublet as input

The estimation results of the longitudinal aerodynamic parameters are displayed in Tab. 2, and the arithmetical mean value of each parameter will be used to generate the longitudinal model of Vector-P that it will be used in the model validation.

Table 2. Estimated and the average values of parameters

	C_{L0}	$C_{L\alpha}$	C_{Lq}	$C_{L\delta e}$	C_{D0}	C_{m0}	$C_{m\alpha}$	C_{mq}	$C_{m\dot{\alpha}}$	$C_{m\delta e}$
Estimation 1	0.507	3.945	3.109	0.321	0.068	-0.081	-0.443	-16.299	6.456	-0.789
Estimation 2	0.381	3.113	3.693	1.152	0.072	-0.066	-0.648	-16.427	1.391	-1.044
Estimation 3	0.685	3.725	3.150	1.370	0.036	-0.113	-0.418	-16.315	2.105	-1.028
Estimation 4	0.522	2.770	2.732	0.984	0.020	-0.081	-0.694	-13.833	-1.967	-1.134
Average Value	0.524	3.388	3.171	0.957	0.049	-0.085	-0.551	-15.719	1.996	-0.999

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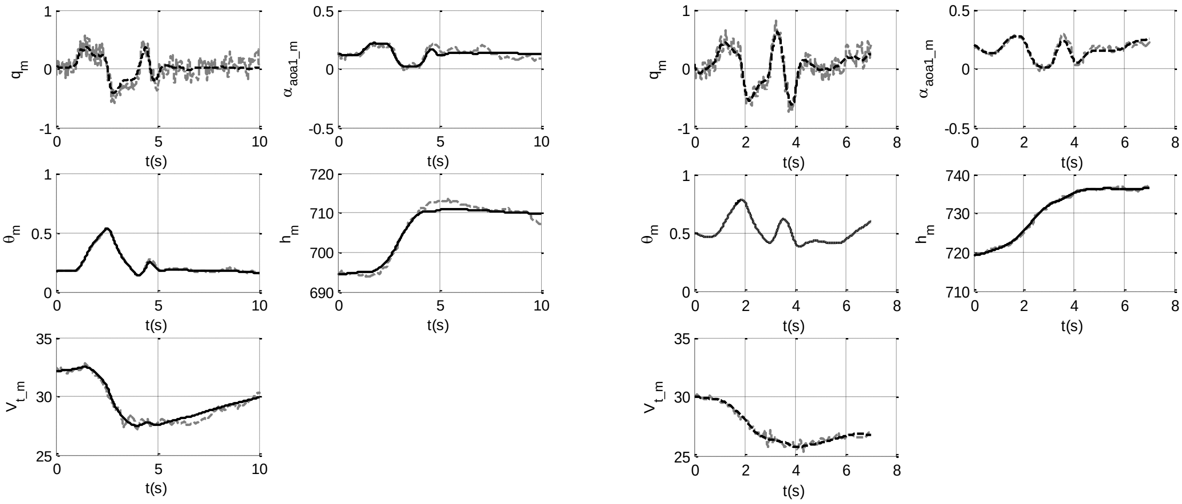

Figure 5. Comparison between flight test data and computed responses containing the estimated parameters and multistep 3-2-1-1 as input

The last computed value of the cost function which is minimized in each identification process is shown in Tab. 3. The values of the determinant of R lower then 10E-10 could be considered as good results, so the final values obtained for each identification process are shown satisfactory *a priori*. The better way to know if the identified model is reliable is to apply some validation criteria.

Table 3. Cost function value.

Process	|R|
1	2.34E-11
2	1.98E-11
3	5.67E-11
4	5.83E-13

It is obtained the identified model with the average values of the estimated parameters whose response is firstly compared with the flight data, as shown in Fig. 6.

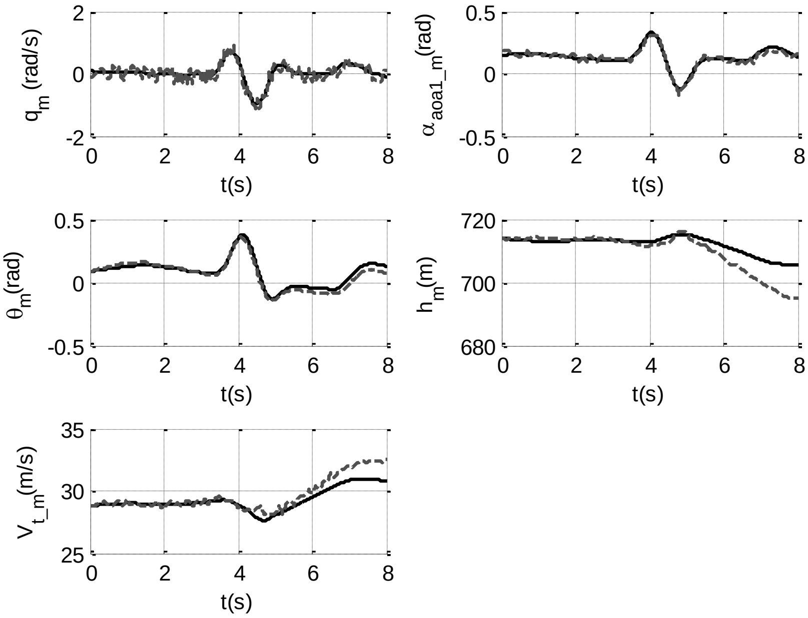

Figure 6. Validation test - Flight test data and identified model response comparison

The first analysis in the validation process is to check the value of the determinant of **R** and, in this case, this value is 6.015E-10. The next result, presented in Tab. 4 is precisely related to the uncertainties of the parameters shown in percentage, whichever is the criterion Cramér-Rao bonds.

Table 4. Parametric deviations obtained through Cramér-Rao bonds criterion.

	Estimated Parameters	Deviations
C_{L0}	0.524	3.17%
$C_{L\alpha}$	3.388	1.25%
C_{Lq}	3.171	3.15%
$C_{L\delta e}$	0.957	6.14%
C_{D0}	0.049	3.49%
C_{m0}	-0.085	3.03%
$C_{m\alpha}$	-0.551	1.72%
C_{mq}	-15.719	0.61%
$C_{m\dot{\alpha}}$	1.996	4.80%
$C_{m\delta e}$	-0.999	0.8%

At this point, it is possible to affirm the identified model can be used in projects that the deviation parameters shown in Tab. 4 is acceptable.

It was applied another validation criterion. Residual analysis was performed by applying the criterion Goodness of Fit, in which the deviation related to the error of each output variable can be calculated and it is displayed in Tab. 5.

Table 5. Output variable deviations

Variable	Deviation	Unit
V	0.63	m/s
θ	0.02	rad
q	0.13	rad/s
α	0.02	rad
H	3.98	m

The identified model can be used for projects that use the dynamic cruise flight where the uncertainty in the altitude of 3.98 meters is permitted. Therefore, this model can be used for steady-flight because the Vector-P flies high enough (above of 50 meters) allowing this deviation value on altitude and this value can be consider as small deviation.

6. AUTOPILOT SIMULATION RESULTS

The response of the aircraft concerning the altitude open loop shows that without autopilot the aircraft does not return to equilibrium condition, as shown in Fig. 7. It was observed good performance in the closed loop simulation, because the aircraft returned to equilibrium condition after few seconds. The cruising speed for the simulation was 33 m/s. The initial condition for the altitude was 650 meters.

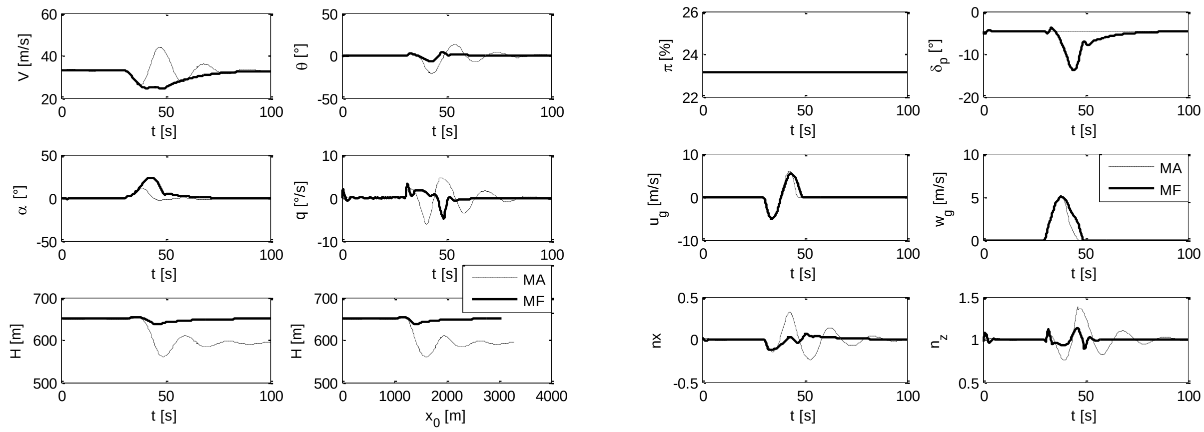

Figure 7. Open loop (MA) and closed loop (MF) system responses comparison

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It is also possible to observe the elevator performance in the closed loop simulation acting to correct the disturbances. It can also check the wind shear components u_g and w_g. The load factors n_x and n_z reached lower amplitudes in closed loop compared with the open loop response.

7. CONCLUSIONS

This study aimed to identify and validate the model of the longitudinal dynamics of Vector-P UAV with experimental data and use this model in the design of an autopilot altitude. The main contributions of this study was to obtain a model of Vector-P identified with data collected in flight campaign, since there were only identifications with simulated data, to present the designed gains to an autopilot architecture, and to test embedded systems in flight campaign.

The identified model was validated as this fulfilled the role of the movement respond accordingly executed in a real flight. To quantitatively evaluate the reliability of the identified model was applied criteria Cramér-Rao Bounds and Goodness of Fit.

A difference between the computed altitude response was observed in altitude with respect to the measurement data. In the investigation of this problem, it was concluded that uncertainties in relation to known parameters such as engine thrust and aircraft inertia values, may have influenced the outcome of the model identification, since the program identification is extremely dependent on a number of input parameters that if values are placed uncorrelated with reality, the values of the parameters identified have no validity.

Another problem is the limitation found in the experiments. The identification was done with the data acquisition some sensors were available. Making identification more types of sensors, such as accelerometers, and use certain variables calculated from flight data may improve the results obtained in identification.

The flight simulation shows that, using the control structure presented of this paper and the projected earnings, it is possible to track the altitude. It was observed that in the simulation result with autopilot the controls operate effectively to correct all disturbances improving aircraft performance.

8. ACKNOWLEDGEMENTS

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10. RESPONSIBILITY NOTICE

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