MODEL-BASED-DESIGN OF AN AIRCRAFT AUTO-PILOT CONTROLLER

Daniel da Motta, daniel.damasceno@embraer.com.br
ITA, Praça Marechal Eduardo Gomes, 50, S. J. Campos, Brazil

Alvaro Vitor Polati, alvaro.souza@embraer.com.br
EMBRAER, Av. Brigadeiro Faria Lima 2170, S. J. Campos, Brazil

Roberto Kawakami, kawakami@ita.br
ITA, Praça Marechal Eduardo Gomes, 50, S. J. Campos, Brazil

Abstract. *The investigation of techniques for improvement of project efficiency is essential to the survival of any corporation. In this context, the present work proposes the use of Model-Based-Design to reduce development cycles and cost of systems development. More specifically, this work brings an example of Model-Based-Design application in the design of an auto-pilot controller. This case study comprises plant modeling, requirements specification, controller design and system verification and validation, highlighting the advantages obtained by the use of models to increase the maturity level of requirements specification.*

Keywords*: Model-Based-Design, Auto-Pilot, Flight Controls*

1. INTRODUCTION

The corporation that develops and delivers aircrafts before the other players has a competitive advantage that is often decisive. As the development phase demands a large quantity of designs, reducing the time spent in each one is essential. A great part of this time is expended to fix mistakes in system implementations due to erroneous specifications. In the traditional design approach, tests can be done only after a prototype has been produced, the system is created from documents in natural language and these documents present low traceability to the requirements. As a result, specification errors may only be found in later stages, increasing the design costs [1], [2].

To overcome this problem, the industry is migrating to a model-based-design (MBD) approach. With MBD, a representation of the system is created using simulation models. The simulation models allow earlier tests of the design, high traceability of the requirements and reuse of test cases. All this increases the discovery of errors in early phases of project, leading to a reduction of design time and costs, with an overall gain of productivity [3].

In short, the traditional way to develop systems presents the advantage of being well-known. On the other hand, as it is based on documents written in natural language, it brings an inherent source of errors due to the human interpretation of these documents. Considering the whole cycle of system development, MBD is faster, cheaper and displays better performance. However, it is important to highlight that MBD requires an extensive use of software tools to automate design processes, resulting in an increase of costs associated to data storing, net resources and software licenses [4],[5],[6].

The main advantages of MBD adoption are more easily realized when the prototypes present high costs, the projects are complex, subject to governmental regulation, need a proof of concept and can harm people in case of failure [2]. This is the typical case of aeronautical industry.

This work presents a case study of model-based-design for an aircraft auto-pilot controller. The design cycle is followed from the requirements specification until the verification and validation phase. The Linear-Quadratic Regulator (LQR) method was adopted to calculate the controller gains. In addition, the LQR weights were tuned by an optimization procedure in order to achieve the performance requirements.

The remaining sections of this paper are organized as follows. Section 2 describes the aircraft model employed in the case study. Section 3 presents the design procedure employed to obtain the controller. Section 4 discusses issues related to design verification and validation. Finally, concluding remarks are given in Section 5.

2. AIRCRAFT MODEL

In this work, a simplified longitudinal model for a twin-engine transport aircraft is employed. The model represents a non-linear stable aircraft, with equations of motion expressed with respect to the aerodynamic reference system [7], [1], as shown in Eq. (1). A description of drag polar, propulsion system and atmosphere features were also extracted from references [7].

$$\begin{cases} \dot{V} = \dfrac{\left(-D - m\,g\sin(\gamma) + T\cos(\alpha + \alpha_F)\right)}{m} \\ \dot{\gamma} = \left(\dfrac{L - m\,g\cos(\gamma) + T\sin(\alpha + \alpha_F)}{mV}\right) \\ \dot{q} = \dfrac{(M_A + M_T)}{I_{yy}} \\ \dot{\alpha} = q - \dot{\gamma} \\ \dot{H} = V\sin(\gamma) \end{cases} \tag{1}$$

The aircraft model inputs are elevator deflection (δP) and thrust (δPI), as can be seen in Figure 1. This figure also brings the controller structure that will be explained further.

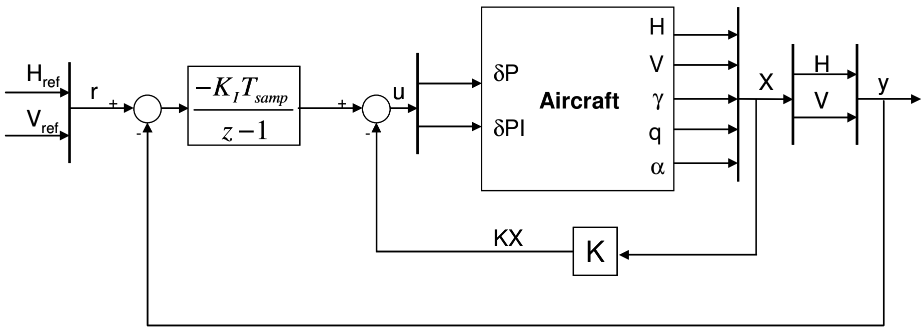

Figure 1. Closed-loop system

For design purposes, the model was linearized in a specific operating point inside the envelope presented in Figure 2.

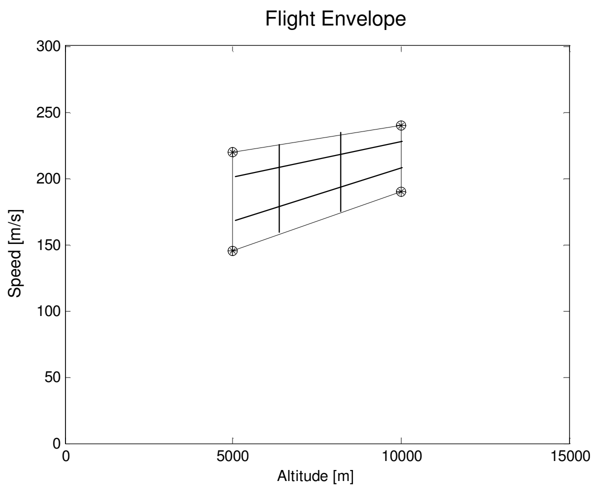

Figure 2. Flight envelope

In this work, the auto-pilot controls the aircraft from a steady flight without wind disturbance. So, to trim the aircraft, it is necessary select just altitude (H) and speed (V) initial conditions, once the trajectory angle (γ) and pitch rate are null. The angle of attack (α), elevator (δ_P) and thrust (δπ) are obtained during the point of equilibrium calculus.

3. CONTROLLER DESIGN

3.1. Control Law

The controller was designed based on the performance requirements (MBD-4 to MBD-11) specified in the appendix. The controller structure can be seen in Figure 1. A linear-quadratic-regulator (LQR) with integral action was employed [7]. In this case, the control law consists of full state feedback with gains that minimize a cost functional of the form.

$$J = \frac{1}{2}\int_0^{\infty}\left[X^T(t)QX(t) + u^T(t)Ru(t)\right]dt \qquad (2)$$

where Q ≥ 0 and R > 0 are weight matrices selected by the designer. In the present work, these matrices were tuned in order to minimize a separate cost function composed by the performance requirements. This cost function is the sum of the contributions of all performance goals (settling time, overshoot and rise time considering a step input in commanded altitude or speed) that exceed the requirements. For example, considering the requirement MBD-4, if the simulation results in a rise time higher than 12s, the cost function adds this value multiplied by a weight, but if the simulation results in a rise time lower than 12s, the cost function adds the value zero. This way, the minimum value of the cost function is that results in the best requirements accomplishment.

To solve the minimization problem was used the fminsearch algorithm of the Matlab Optimization Toolbox.

Due the advantages as less sensibility to parametric changes and the possibility of implement more complex control laws, the controller implementation will be discrete. It was selected the zero-order-hold (ZOH) as discretization method. To obtain a similar control loop behavior using the continuous and the discrete controller, the controller sampling time was defined as 25 Hz, a frequency greater than twice the passband of the fastest system mode.

3.1. Controller Logics

In this design, the auto-pilot is not engaged during all flight time, just during the cruise phase. Intending to select the auto-pilot engagement, this controller logics module of Figure 3 was inserted in the model. It was designed based on the requirements (MBD-14 to MBD-18) presented in the appendix.

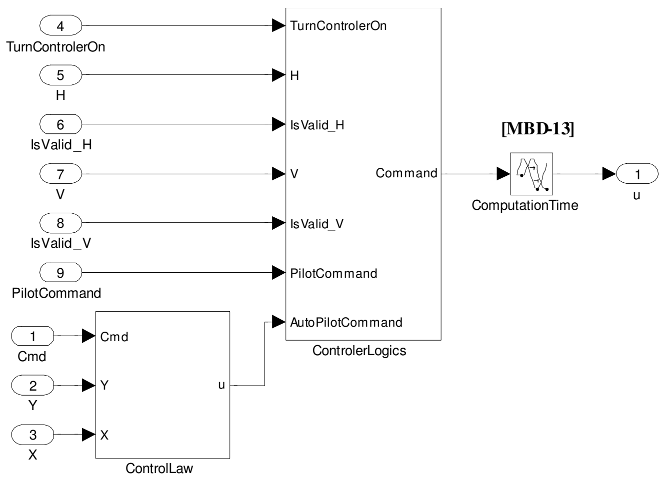

Figure 3. Auto-pilot Controller

4. DESIGN VERIFICATION AND VALIDATION

In this work, verification is formed by the processes and techniques that the model developer uses to assure that his model is correct and matches any agreed-upon specifications and assumptions. Validation refers to the processes and techniques that the model developer, model customer and decision makers jointly use to assure that the model represents the real system (or proposed real system) to a sufficient level of accuracy [11]-[16].

4.1. Performance requirements V&V

Intending to verify that the aircraft with the proposed auto-pilot is able to reach the performance requirements, the closed-loop system was simulated in the four corners of the flight envelope. Table 1 presents the test case number, the tested requirement, flight envelope corner, the applied input and the criteria that must be accomplished.

Table 1. Performance Tests Specification

TestCase	Requirement	Flight Condition [V,γ,q,H]	Input	Criteria
1	MBD-4	[145m/s,0°,0°/s,5000m]	H_{Step} =30m	Tr_H <12s
2	MBD-5	[145m/s,0°,0°/s,5000m]	H_{Step} =30m	Ts_H <45s
3	MBD-7	[145m/s,0°,0°/s,5000m]	H_{Step} =30m	Mp_H <30%
4	MBD-8	[145m/s,0°,0°/s,5000m]	V_{Step} =15m/s	Tr_V <12s
5	MBD-9	[145m/s,0°,0°/s,5000m]	V_{Step} =15 m/s	Ts_V <45s
6	MBD-11	[145m/s,0°,0°/s,5000m]	V_{Step} =15 m/s	Mp_V <30%
7	MBD-4	[220m/s,0°,0°/s,5000m]	H_{Step} =30m	Tr_H <12s
8	MBD-5	[220m/s,0°,0°/s,5000m]	H_{Step} =30m	Ts_H <45s
9	MBD-7	[220m/s,0°,0°/s,5000m]	H_{Step} =30m	Mp_H <30%
10	MBD-8	[220m/s,0°,0°/s,5000m]	V_{Step} =15 m/s	Tr_V <12s
11	MBD-9	[220m/s,0°,0°/s,5000m]	V_{Step} =15 m/s	Ts_V <45s
12	MBD-11	[220m/s,0°,0°/s,5000m]	V_{Step} =15 m/s	Mp_V <30%
13	MBD-4	[190m/s,0°,0°/s,10000m]	H_{Step} =30m	Tr_H <12s
14	MBD-5	[190m/s,0°,0°/s,10000m]	H_{Step} =30m	Ts_H <45s
15	MBD-6	[190m/s,0°,0°/s,10000m]	H_{Step} =30m	Mp_H <5%
16	MBD-8	[190m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Tr_V <12s
17	MBD-9	[190m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Ts_V <45s
18	MBD-10	[190m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Mp_V <5%
19	MBD-4	[240m/s,0°,0°/s,10000m]	H_{Step} =30m	Tr_H <12s
20	MBD-5	[240m/s,0°,0°/s,10000m]	H_{Step} =30m	Ts_H <45s
21	MBD-6	[240m/s,0°,0°/s,10000m]	H_{Step} =30m	Mp_H <5%
22	MBD-8	[240m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Tr_V <12s
23	MBD-9	[240m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Ts_V <45s
24	MBD-10	[240m/s,0°,0°/s,10000m]	V_{Step} =15 m/s	Mp_V <5%

The Figures 4-11 and the Tables 2-7 present the simulation results to each test case presented before.

Table 2. TestCases

[V,γ,q,H] = [145,0,0,5000], H_{Step} =30 m			
TC	**Req**	**Criteria**	**PF**
1	MBD-4	Tr_H <12s	1
2	MBD-5	Ts_H <45s	1
3	MBD-7	Mp_H <30%	1

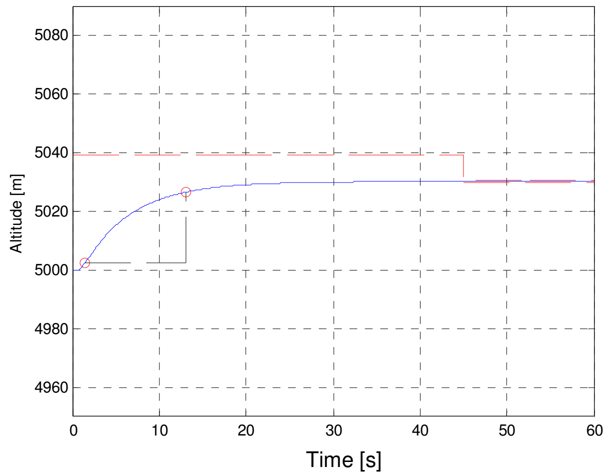

Figure 4. TestCase results 1-3

Table 3. TestCases

[V,γ,q,H] = [145,0,0,5000], V_{Step} =15 m/s			
TC	**Req**	**Criteria**	**PF**
4	MBD-8	Tr_V <12s	1
5	MBD-9	Ts_V <45s	1
6	MBD-11	Mp_V <30%	1

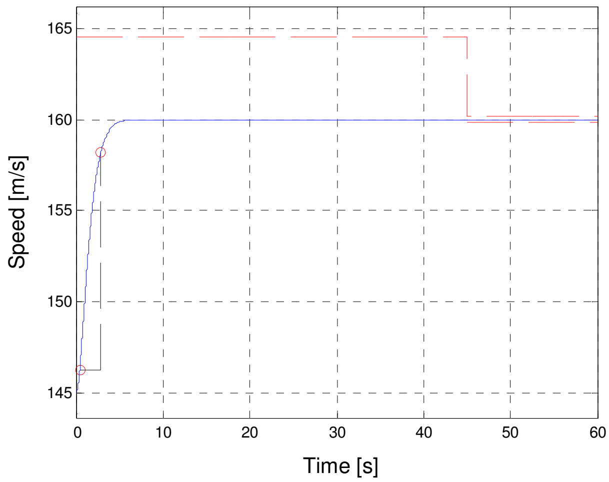

Figure 5. TestCase results 4-6

Table 4. TestCases

[V,γ,q,H] = [220,0,0,5000], H_{Step} =30 m			
TC	**Req**	**Criteria**	**PF**
7	MBD-4	Tr_H <12s	1
8	MBD-5	Ts_H <45s	1
9	MBD-7	Mp_H <30%	1

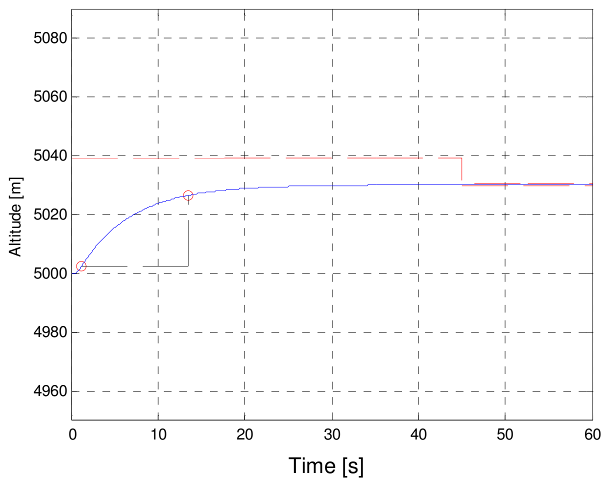

Figure 6. TestCase results 7-9

Table 5. TestCases

[V,γ,q,H] = [220,0,0,5000], V_{Step} =15 m/s			
CT	**Req**	**Criteria**	**PF**
10	MBD-8	Tr_V <12s	1
11	MBD-9	Ts_V <45s	1
12	MBD-11	Mp_V <30%	1

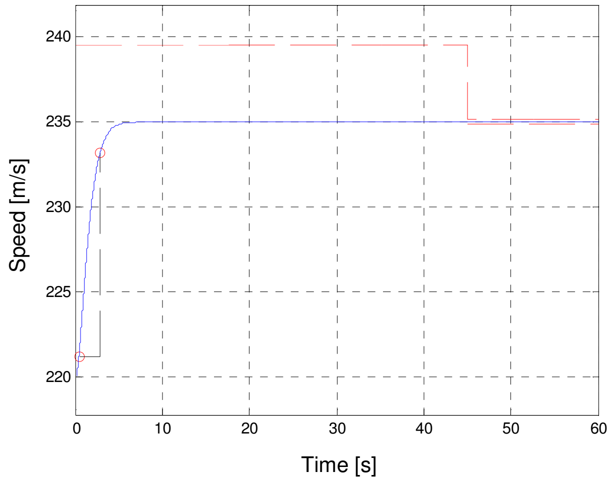

Figure 7. TestCase results 10-12

Table 6. TestCases

[V,γ,q,H] = [190,0,0,10000], H_{Step} =30 m			
CT	**Req**	**Criteria**	**PF**
13	MBD-4	Tr_H <12s	1
14	MBD-5	Ts_H <45s	1
15	MBD-7	Mp_H <5%	1

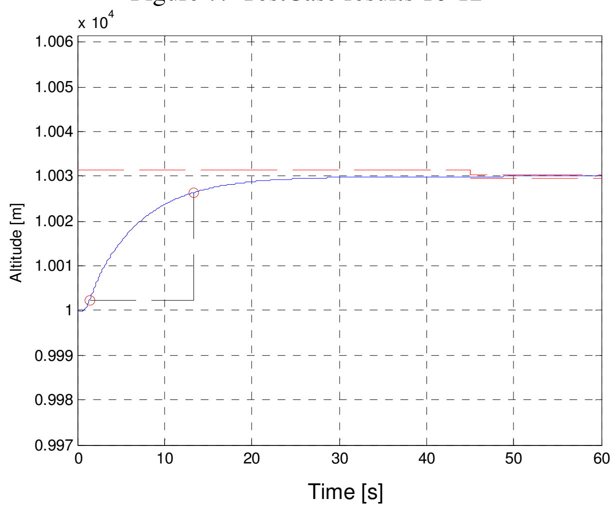

Figure 8. TestCase results 13-15

Table 7. TestCases

[V,γ,q,H] = [190,0,0,10000], V_{Step} =15 m/s			
CT	**Req**	**Criteria**	**PF**
16	MBD-8	Tr_V <12s	1
17	MBD-9	Ts_V <45s	1
18	MBD-11	Mp_V <5%	1

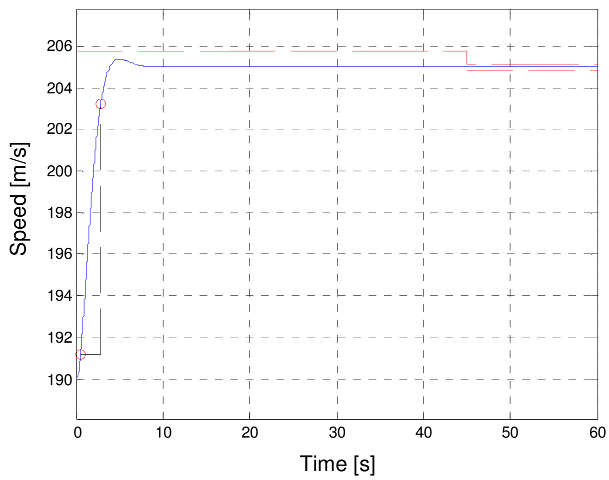

Figure 9. TestCase results 16-18

Table 8. TestCases

[V,γ,q,H] = [240,0,0,10000], H_{Step} =30 m			
CT	**Req**	**Criteria**	**PF**
19	MBD-4	$Tr_H<12$	1
20	MBD-5	$Ts_H<45$	1
21	MBD-7	$Mp_H<5\%$	1

Time [s]

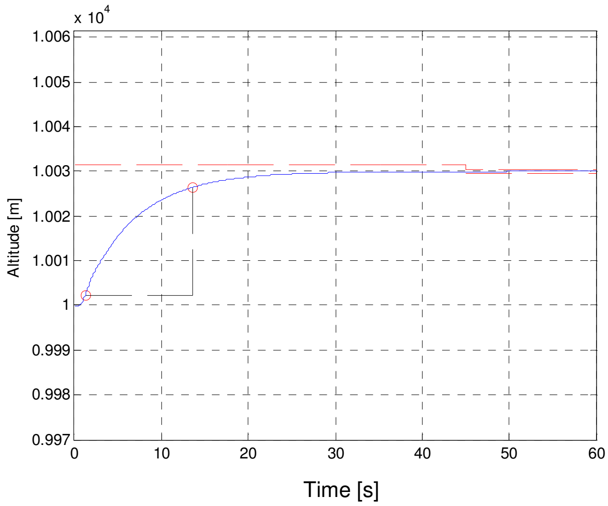

Figure 10. TestCase results 19-21

Table 9. TestCases

[V,γ,q,H] = [240,0,0,10000], V_{Step} =15 m/s			
CT	**Req**	**Criteria**	**PF**
22	MBD-8	$Tr_V<12$	1
23	MBD-9	$Ts_V<45$	1
24	MBD-11	$Mp_V<5\%$	1

Time [s]

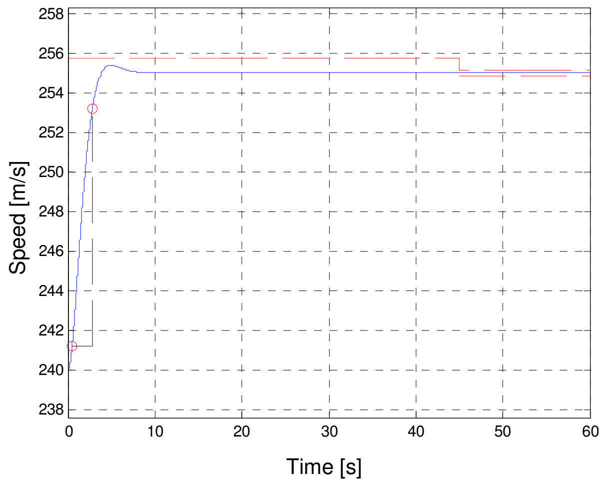

Figure 11. TestCase results 22-24

As can be seen in these simulation results, the controller passed in all tests established by the performance requirements.

4.2. Functional requirements V&V

The V&V of the controller functional requirements will also be based in testing the simulation model.

The first functional requirement that can be tested is the MBD-15. Analyzing the requirement statement, it is possible to realize that the requirement specifies the output only when ControlerOnH is true, neglecting the situation when the output signal is false. So the implementation in Matlab/Simulink presented in , with its test presented in , pass in the verification phase. However, this simulation analyses concludes that MBD-15 is incomplete, once the value of the signal isValid_H is irrelevant to the output of ControlerOn. With this result, the requirement does not pass in the validation phase.

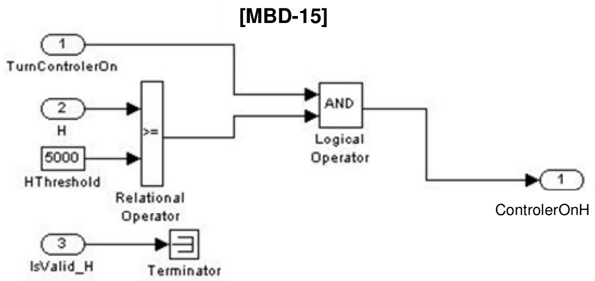

Figure 12. MBD-15 implementation in Simulink

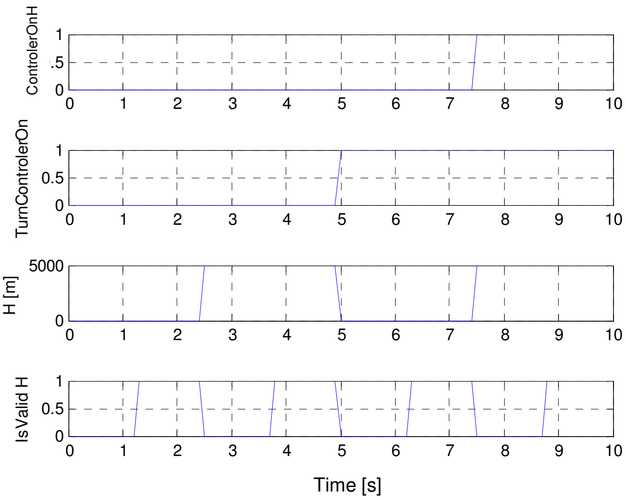

Figure 13. MBD-15 simulation result

Thus, it is necessary to specify a new requirement that considers the situation when the altitude measure is invalid. This requirement is presented below:

[MBD-19] The output ControlerOnH shall be false, if the altitude measure is invalid (isValid_H = 0), despite of the auto-pilot engagement command and the altitude measure value.

The new implementation, considering MBD-15 and MBD-19 is presented in , and its test is shown in . Now these set of requirements attend this design needs, and the specifications pass in the verification and validation phase.

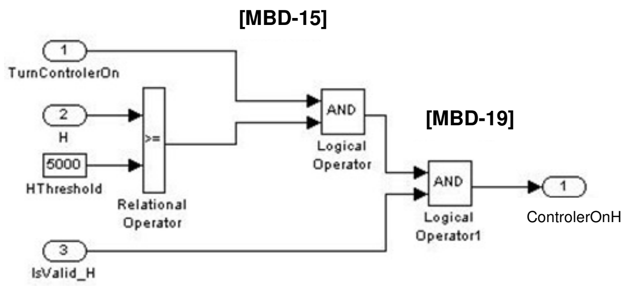

Figure 14. MBD-15 and MBD-19 implementation

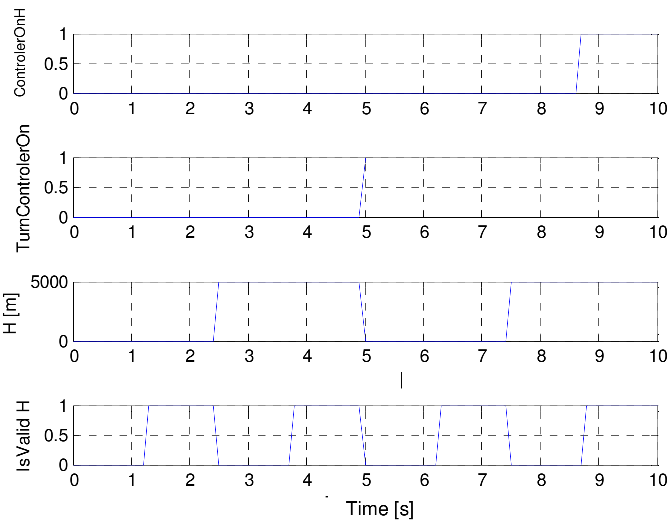

Figure 15. MBD-15 and MBD-19 simulation results

The other functional requirements, which regard to aircraft speed conditions to engage the auto-pilot, are very similar to the statement presented in the requirements MBD-15 and MBD-19 and their verification and validation will not be presented.

5. CONCLUSION

This work presented a model-based-design of an auto-pilot controller starting in the aircraft modeling, passing through the controller design and its verification and validation.

After the aircraft modeling, it was designed the controller based on an initial set of requirements. The controller was designed using the LQR method. The weights (Q and R matrices) were calculated using an optimization routine that calculates the matrices based on the performance requirements.

The last step was the verification and validation of the design. In this phase, it was discovered an error in the controller functional requirements. The controller was redesigned and then was presented the results of the closed-loop system to show that the closed-loop system accomplished the requirements.

So, this paper presented an example of an increase in the maturity level of the system requirements before the system implementation. This represented two main advantages: cost reduction and development time reduction.

6. REFERENCES

[1] NATIONAL. INSTRUMENTS. **Shortening the embedded design cycle with model-based-design**. 2006. Disponível em: <http://zone.ni.com/devzone/cda/tut/p/id/4074>. Acesso em: 01 Jun. 2009.

[2] KRASNER, J. **Model-based design and beyond:** solutions for today embedded systems requirements. Embedded Market Forecasters, 2004. Disponível em: <http://www.mathworks.com/mason/tag/proxy.html?dataid=4484&fileid=17878>. Acesso em: 01 Jun. 2009.

[3] SMITH, P.F.; PRABHU, S.M.; FRIEDMAN, J.H. Best practices for establishing a model-based design culture. In: SAE WORLD CONGRESS, 2007, Detroit. **Proceedings…** Warrendale, Pa. : Society of Automotive Engineers, 2007.

[4] BHATT, D. et al. Model-based development and the implications to design assurance and certification. In: DIGITAL AVIONICS SYSTEMS CONFERENCE, 2005. .**Proceedings…**New York: IEEE, 2005. v.2.

[5] BAKER, L. et al. Foundational concepts for Model Driven System Design. [S. l.]: INCOSE MODEL DRIVEN SYSTEMS DESIGN WORKING GROUP, 1997. White paper.

[6] BARNARD, P. Software development principles applied to graphical model development. In: AIAA MODELING AND SIMULATION TECHNOLOGIES CONFERENCE AND EXHIBIT, 2005. **Proceedings…**Washington, DC: AIAA, 2005.

[7] STEVENS, B. L; LEWIS, F. L. **Aircraft control and simulation.** 2. ed. Hoboken: John Wiley Professional, 2003.680p.

[8] HELMERSSON, A. et al. **Robust flight control design challenge, problem formulation and manual**: The Research Civil Aircraft Model (RCAM). GARTEUR/TP-088-03, 1996.

[9] RAUW, M. **FDC 1.2:** a simulink toolbox for flight dynamics and control analysis. 2.ed. May.2001. Disponível em: <http://www.dutchroll.com>. Acesso em: 01 Jun, 2009.NORTH ATLANTIC TREATY ORGANIZATION**.** **Flight control design:** best pratices. Neuilly-Sur-Seine:, 2000. (RTO Technical Report, 029). Disponível em: <http://ftp.rta.nato.int/public//PubFulltext/RTO/TR/RTO-TR-029///TR-029-$$TOC.pdf>. Acesso em: 08 out 2008.

[10] NORTH ATLANTIC TREATY ORGANIZATION**.** **Flight control design:** best pratices. Neuilly-Sur-Seine:, 2000. (RTO Technical Report, 029). Disponível em: <http://ftp.rta.nato.int/public//PubFulltext/RTO/TR/RTO-TR-029///TR-029-$$TOC.pdf>. Acesso em: 08 out 2008.

[11] BALCI, O. et al. Expanding our horizons in verification, validation, and accreditation research and practice. In: WINTER SIMULATION CONFERENCE, New Orleans, 2003. .**Proceedings…** Monterey, CA: WSC Foundation, 2003.

[12] SARGENT, R.G. Verification and validation of simulation models. In: WINTER SIMULATION CONFERENCE, 2007. **Proceedings…** Monterey, CA: WSC Foundation, 2007.

[13] CARSON II, J.S. Model Verification and validation. In: WINTER SIMULATION CONFERENCE, 2002.**Proceedings…** Monterey, CA: WSC Foundation, 2002.

[14] LAW, A. M. MCCOMAS, M.G. How to build valid and credible simulation models. In: WINTER SIMULATION CONFERENCE, 2001. **Proceedings…** Monterey, CA: WSC Foundation, 2001.

[15] LAW, A. . How to build Valid and Credible Simulation Models. In: WINTER SIMULATION CONFERENCE, 2005. **Proceedings…** Monterey, CA: WSC Foundation, 2005.

[16] VV&A. **Fidelity report**. Sep. 2000. Disponível em: <http://vva.msco.mil/Special_Topics/Fidelity/fidelity-pr.pdf >. Acesso em: 01 Jun. 2009.

7. APPENDIX

System requirements:

[MBD- 1] The controller shall be able to control the aircraft altitude.

[MBD- 2] The controller shall be able to control the aircraft speed.

[MBD- 3] The controller shall be discret.

[MBD- 4] The system (controller + aircraft) shall follow a 30 m altitude step, from a steady level flight in the flight envelope specified in Figure 2: with rise time Tr less than 12s;

[MBD- 5] And settling time Ts less than 45s based on 1% criteria;

[MBD- 6] And overshoot Mp less than 5%, in altitudes higher than 7500m;

[MBD- 7] And overshoot Mp less than 30%, in altitudes less than 7500m.

[MBD- 8] The system (controller + aircraft) shall follow a 15m/s speed step, from a steady level flight in the flight envelope specified in Figure 2: with rise time Tr less than 12s;

[MBD- 9] And settling time Ts less than 45s based on 1% criteria;

[MBD- 10] And overshoot Mp less than 5%, in altitudes higher than 7500m;

[MBD- 11] And overshoot Mp less than 30%, in altitudes less than 7500m.

[MBD- 12] The controller will not consider wind disturbance in its design.

[MBD- 13] The system shall be in compliance with the perfomance requirements considering a 26ms time delay due the control law computation time.

[MBD- 14] The controller shall control the aircraft only when the ControlerOn signal is true.

[MBD- 15] The output signal ControllerOnH shall be true, if the altitude measure was valid (IsValid_H = 1), if the altitude measure was higher than 5000 m (H > 5000 m) and the pilot commands the auto-pilot engagement (TurnControlerOn = 1).

[MBD- 16] The output signal ControllerOnV shall be true, if the speed measure was valid (IsValid_V = 1), if the speed measure was higher than 145 m/s (V > 145 m/s) and the pilot commands the auto-pilot engagement (TurnControlerOn = 1).

[MBD- 17] The output signal ControllerOnV shall be false, if the speed measure was invalid (IsValid_V = 0), despite of the auto-pilot engagement command and the speed value.

[MBD- 18] The output signal ControllerOn shall be true, only if the ControlerOnH signal and ControlerOnV signal were true.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the material included in this paper.