Analog Filter Realization for Human - Machine Interaction in Aerospace

Jan BORIL, Karel ZAPLATILEK, Rudolf JALOVECKY
University of Defence, Faculty of Military Technology
Kounicova 65, Brno 662 10, Czech Republic
jan.boril@unob.cz, karel.zaplatilek@unob.cz, rudolf.jalovecky@unob.cz

Abstract—Mathematical models of human behavior while flying an aircraft have been created for testing the physical and psychological state of pilots in aerospace. These models vary, but often they are characterized by a linear model with transport delay. Time constants in these models represent basic pilot skills, experience, and neuromuscular properties of a human. This article describes one of these mathematical models shown as a rational fraction function. The main purpose of this article is to analyze this model from the realization or implementation point of view. Two implementation methods are described here. The first is based on a state-space description using integrator synthesis. The second method is a physical circuit realization using active analog ARC filters. A model is created in the Simulink system to verify the state-space implementation. Parameters of this system are set automatically in the MATLAB environment. The analog realization part completes the previously published study of filter optimization. Together these articles make a complete research system of studies from pilot response tests to optimal model realization.

Keywords— Human-machine interaction, pilot behavior model, mechatronic system pilot–aircraft, analog filter realization, MATLAB®, Simulink®.

I. INTRODUCTION

Let's ask a question right at the beginning: Why are there still a lot of car and aircraft accidents when current technologies are getting more sophisticated, having modern electronic equipment with multiple backups and built-in diagnostic devices? The answer is simple – the human factor. The human and his behavior while controlling a machine, driving a car or piloting an aircraft. The human factor is generally described and defined by many scientists using the SHELL model [1]. The SHELL model consists of several parts and this article focuses on the interaction part – the interaction between the human (L - Liveware, in the middle of the model) and the machine (H - Hardware).

Human behavior is too complicated to be described by simple mathematical models. Variable human characteristics don't allow one simple universal mathematical description fully characterizing his dynamic characteristics at different activities. It is even harder to create mathematical models of a human-pilot while flying an aircraft. It is a very difficult and extensive task to determine the optimal substitute mathematical model for an automated regulation system. This is because the parameters and pilot (human) time constants are time variables and dependent on many unpredictable factors [2], such as flight experience, tiredness, stress, noise, etc.

Human behavior models, expressed by parameters of automated regulation, have been in literature for several years. In early years, these models were based only on assumptions of options for human behavior when controlling a machine. Later, with the advancement of information technology – especially using simulation tools MATLAB and Simulink, the early assumptions were confirmed and specified. One such proof of human behavior model use when controlling a machine is found in Dissertation Thesis [3]. This thesis describes the human behavior model while driving a car, i.e. machine movement in 2D. Flying an aircraft requires 3D. The mathematical model of human behavior while flying an aircraft, as used here, was described and published, for example, in [4].

II. MATHEMATICAL MODELS OF HUMAN BEHAVIOR

The basis, for creating sufficiently representative models of human behavior while controlling a machine, is human dynamics. From the automated regulation point of view, human behavior can be described by a relatively simple block diagram, see Fig. 1. Basically, there are three serially connected blocks.

- The linear block - representing sensory organs and being the input signal for the model.
- The non-linear block - must be divided into a block with limited range (arm length, leg length for pedal control) and a block with transport delay – the human response time to an external stimulus.
- The last block at the output end is the Power Member, representing the possible human force to create movement (pressure to the control yoke or pedals).

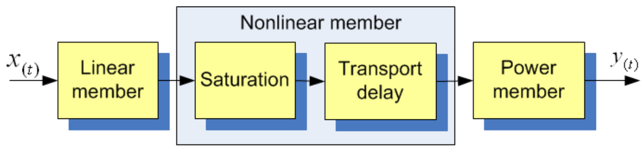

Figure 1. One of the possible models of human behavior while controlling a machine

A lot of scientific articles [5-6] describe possible approaches to creating human behavior mathematical models. They are based on long-term experiments followed by

978-1-5090-2152-9/16/$31.00 ©2016 IEEE

response analyses to the input information. The American scientists McRuer and Krendel were tried to find out, without simulation tools, a physiological interpretation of the corresponding time constants [7]. In experiments with a human behavior model a linearized model with transport delay is often used and represented by the following transfer function:

$$F(s)=\frac{Y(s)}{X(s)}=K\frac{(T_3s+1)}{(T_1s+1)(T_2s+1)}e^{-\tau s} \quad . \qquad (1)$$

Where:

K Pilot gain represents pilot habits for a given type of aircraft control. If the pilot over - intervenes or there is a change in system amplification during the regulatory process, the system could become unstable.

T_1 Lag time constant is related to the implementation of learned stereotypes and pilot routines. When the pilot repeats certain situations several times, it leads to stereotypes and learned habits. The phase arrives when the pilot gradually eliminates his brain activity.

T_2 Neuromuscular lag time constant represents the pilot's delay in an activity which is performed by the neuromuscular system. The neuromuscular system in its entirety includes muscles and sensory organs working at the spinal level (spinal cord). Through the spinal cord the brain receives information and can react to the external environment. The central nervous system and peripheral nervous system provide information links between the organism and the external environment and continuously regulates processes within the body.

T_3 Lead time constant is related to the experience of the pilot. Reflecting the pilot's ability to predict a control input which means to predict the situation that may occur. To estimate and predict the future state is the ability to imagine the future steps and states of the surrounding area. This level represents the highest level of situational awareness where the pilot has gained such knowledge of the state and dynamics of the individual system elements that he has the ability, not only to understand the current situation, but also to determine the future situation. The pilot obtains this level of ability via training and experience.

τ This time constant indicates the delay of brain response to the pilot's musculoskeletal system and eye perception. The transport delay depends on the current state of the neuromuscular system and also on the physical and mental condition. The transport delay value may significantly increase due to fatigue and the regulatory system could become unstable [8].

III. Flight Simulator Description and Test Methods

Flight parameters, later used for parameter optimization of the transfer function [9], were measured on a Cessna 152 Cockpit Simulator (Fig. 2). The Cessna 152 flight simulator consists of a Cessna 152 aircraft fuselage with two seats for crew. This fuselage is anchored to a static base fixed to the floor. Flight visualization is performed by three projectors, projecting images onto a parabolic wall. Based on the research needs, X-Plane 9 software from the Laminar Research Company was used. The flight simulator, as a whole, is controlled by a PC, the so called Instructor Station. An instructor sitting at this station can change any flight parameters during the flight simulation. All controls and control instruments inside the cockpit are connected to the instructor station.

The tested pilots were around the age of 23 and all holding Commercial Pilot Licenses (CPL). They all had several hours of flight experience in Cessna 152 and Cessna 172 aircrafts. The authors of this article chose a flight altitude change as the input signal, to which the pilot responded by controlled yoke movement. The yoke movement in a horizontal plane was recorded and the data was used as output data.

After an initial induction and simulator training the test procedure and task were explained to the pilot. The pilot was required to maintain the plane at a straight horizontal flight. The instructor suddenly decreases the aircraft altitude by 100 feet. In a real life situation such a decrease in altitude could be caused by strong weather conditions or turbulence. The pilot's task was to return the aircraft back to the original altitude as quickly as possible and remain there. He could do this only by using the aircraft elevator. The engine thrust was kept constant. The test was repeated several times with the same pilot. Other pilots were tested in the same way. All data was recorded on the computer of the Instructor's station.

Initially the pilots reacted to the sudden step change of altitude by rapid control yoke movement in order to get the aircraft back to the previous flight level as soon as possible. Therefore, the graphs tended to have some overshoots in the altitude amplitude. As the tests progressed, the pilots gained experience and made their corrective action more efficient, thus shortening the time needed for the whole maneuver. The best test maneuver was selected for this article and then analyzed.

Figure 2. Cessna 152 Cockpit Simulator (University of Hertfordshire)

IV. Filter Realization Using State - Space Approach

Filter transfer function (1), without transport delay τ, can be re-written for a better filter type identification as:

$$F(s)=\frac{KT_3s+K}{T_1T_2s^2+(T_1+T_2)s+1}=\frac{A_3s+A_4}{s^2+A_1s+A_2}, \tag{2}$$

$$A_1=\frac{T_1+T_2}{T_1T_2},\ A_2=\frac{1}{T_1T_2},\ A_3=\frac{KT_3}{T_1T_2},\ A_4=\frac{K}{T_1T_2}.$$

According to (2) it is the 2nd order analog frequency filter. It is not an ordinary filter type due to its non-standard numerator. To realize the filter the following adjustments had to be made according to the block diagram in Fig. 3.

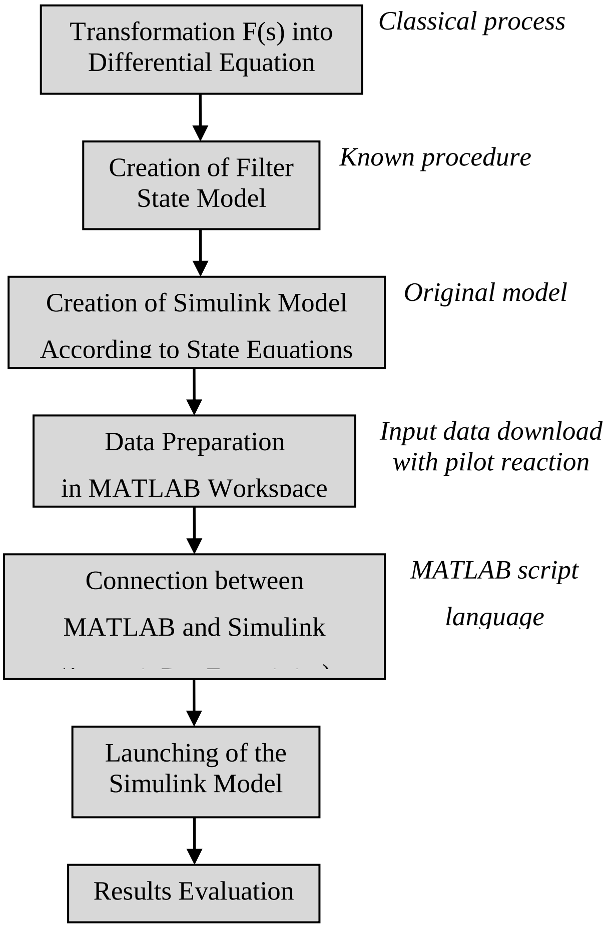

Figure 3. Block diagram of the state-space model creation

First, equation (2) was transformed into a differential equation of 2nd order by a standard procedure [10]:

$$\frac{d^2y}{dt^2}+A_1\frac{dy}{dt}+A_2y=A_3\frac{dx}{dt}+A_4x. \tag{3}$$

Then, the formula needed to be transformed into state model form. Again, a standard procedure was used, substituting [10-12]:

$$\frac{dy_1}{dt}=y_2,$$
$$\frac{dy_2}{dt}=-A_1y_2-A_2y_1+A_3\frac{dx}{dt}+A_4x. \tag{4}$$

The state model was created by integration of formulas in (4).

$$y_1=\int_t y_2\,dt+y_1(0),$$
$$y_2=\int_t[-A_1y_2-A_2y_1+A_3\frac{dx}{dt}+A_4x]dt+y_2(0). \tag{5}$$

Variable x represents input data with a step change of flight altitude.

Formulas (5) are the resultant state mathematical model of the analog filter (1), or (2). The equation was used for direct block realization in Simulink [11-12].

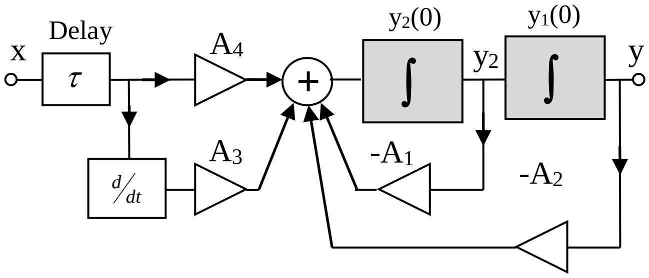

Figure 4. Realization structure of the analog filter state model

Fig. 4 shows the final realization structure of the state model according to (5). It is the result of a typical integrator synthesis [13-15]. The multiplying constants are given by (2). The delay of the *Delay Block* represents the pilot's response and is in accordance with model (1). As mentioned earlier, this is not a standard structure of the 2nd order, this is original modification represented mainly by numerator of the transfer function, see (2).

Fig. 5 shows a particular filter model in the Simulink environment [11-12].

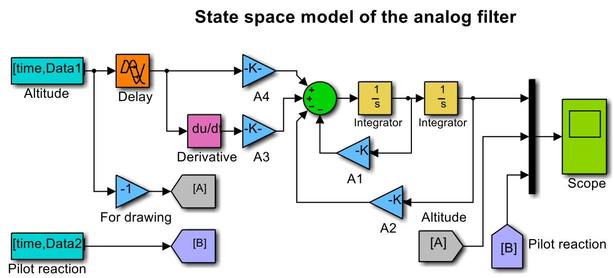

Figure 5. Analog filter state-space model in Simulink

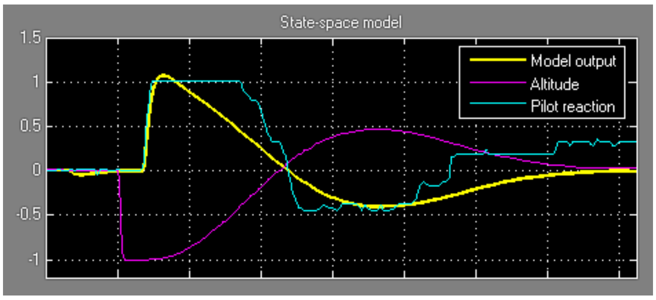

Figure 6. Simulation of the filter state-space model

Fig. 6 shows the aircraft altitude change as input data for the model and also shows the pilot's response (control yoke). The constants were calculated by the optimization algorithm [9]:

$$A_1 = 6{,}4286(s^{-1}),\quad A_2 = 7{,}1429(s^{-2}),$$
$$A_3 = 7{,}1587(s^{-1}),\quad A_4 = 5{,}2381\,(s^{-2}),$$
$$\tau = 0{,}66667\,(s). \tag{6}$$

Data is automatically transferred from MATLAB to the Simulink model, including simulation initiation [16-17]. This advanced and sophisticated method provides a wide spectrum of modeling and simulations options.

To verify the accuracy of the state model simulation, the model in Fig. 4 was complemented by an idealized transfer function as in (1). The simulation results are identical.

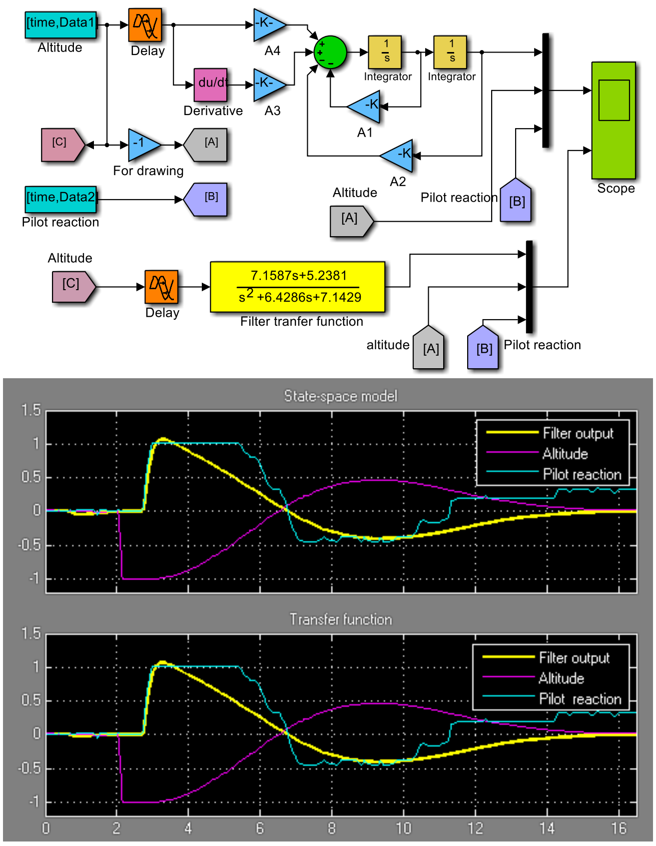

Figure 8. Comparative simulation of the two presented models

V. Filter Realization Using Active ARC Structures

An Optimal Active Filter Synthesis Method is described in this section according to (1) or (2).

As mentioned in section II, this filter is not a standard filter of 2nd order, as the numerator of the transfer function was modified (2). For the synthesis, the transfer function needed to be divided as follows:

$$F(s) = \frac{A_3 s + A_4}{s^2 + A_1 s + A_2}$$
$$= \frac{A_3 s}{s^2 + A_1 s + A_2} + \frac{A_4}{s^2 + A_1 s + A_2}, \tag{7}$$
$$F(s) = BP2 + LP2,$$

where symbols *BP2* and *LP2* represent a band-pass filter and low-pass filter of 2nd order [14]. Thus, this filter is the parallel connection of two filters of 2nd order. This fact serves as the basis for the synthesis of the circuit connections.

The parallel connection of the *LP2* and *BP2* blocks is separated by a unit amplifier *Buffer* to insure minimum output resistance of the input signal source. The sum is done by a standard additive amplifier [15].

Fig. 10 and Fig. 11 are detailed diagrams of *LP2* and *BP2* as ARC filters with operational amplifiers (*Opamp*).

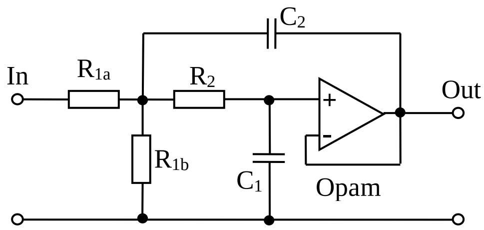

Figure 10. The second-order low-pass ARC filter

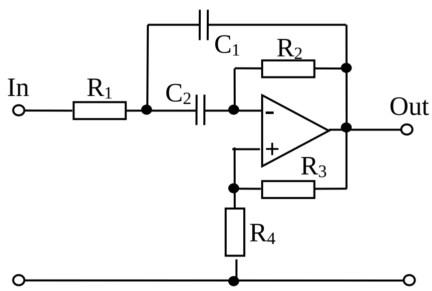

Figure 11. The second-order band-pass ARC filter

To make the particular section proposal simple, the transfer functions (7) were transformed into semi-symbolic formulas:

$$F(s)=\frac{1{,}1135.6{,}4286s}{s^2+6{,}4286s+7{,}1429}+ \\ +\frac{0{,}7333.7{,}1429}{s^2+6{,}4286s+7{,}1429}, \quad (8)$$

where the numerator coefficients and the denominator were calculated from (6).

The multiplying numbers *1,1135* and *0,7333* were realized using amplification (*BP2*), or if you like, the ratio of resistors *R1a, R1b (LP2)*. More detailed component values are not proposed in here, as this is a well-known and published procedure. The realization of an additive amplifier is also not described here, as this is a standard connection [13-15]. However, realization of delay τ is described in (1). An all-pass network of 2nd order, such as an ARC circuit with two operational amplifiers [14], needed to be used. This connection is also well known and thus not described in detail in here.

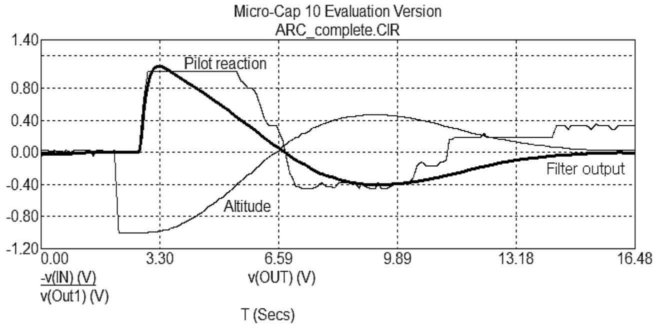

Figure 12. Simulation of the whole ARC filter realization in Micro-Cap

Fig. 12 shows computer simulation results of the complete ARC filter realization structure. The simulation was done in a known professional program Micro-Cap [18]. It is the SPICE compatible software. A complicated Boyle model was used as the model for the operational amplifier, representing a range of realistic amplifier features. The program worked directly with the measured input data (altitude change, tested pilot response).

VI. Conclusion

Two different ways of realizing analog frequency filters, used as pilot response models in aviation, were described in this article. The first method is based on a state-space approach. The realization was created using integrator synthesis. The structure was modeled in the Simulink system environment. The automated control of the Simulink model directly from MATLAB environment was a specialty of this study resulting from its original processing method.

The second realization method was based on using active ARC analog structures. The transfer function of the whole filter was divided into two parallel sections of 2nd order that were synthesized using standard procedures.

Detailed diagrams of low-pass and a band-pass of 2nd order were shown. The realization diagram of the whole filter was simulated in a well-known professional circuit simulator Micro-Cap (SPICE compatible program). In addition, the realization using a Laplace sources, suitable for initial experiments or comparative simulations, was shown too. The specific values of transfer function coefficients of both sections were calculated by an optimization procedure which is not part of this article.

The main reason for realization of this filter was to provide more options for detailed study of responses and reactions that are not easy to get from the non-standard transfer functions. By identifying the basic realization elements, the aim of this study was achieved.

References

[1] F. H. Hawkins, H. W. Orlady, *Human factors in flight*. Second edition. England: Avebury Technical, 1993.

[2] D. C. Foyle, B. L. Hooey, *Human Performance Modeling in AVIATION*. Boca Raton; New York; London; CRC Press, 2008.

[3] M. Havlikova, *Driver Fatigue Simulation (in Czech)*. Elektrorevue, vol. 2010, Nr. 54, 2010.

[4] Jalovecky, R,"Man in the aircraft's flight control system," in *Advance in Military Technology – Journal of Science*. University of Defence, Vol.4. No.1, 2009, pp. 49–57.

[5] M. M. Lone, A. K. Cooke, "Development of a pilot model suitable for the simulation of large aircraft," in *27th International Congress of Aeronautical Sciences 2010*, Paper ICAS 2010-6.7.2, Nice, France, 2010, pp. 1–15.

[6] N. Cameron, D. G. Thomson, D. J. Murray-Smith, "Pilot Modelling and Inverse Simulation for Initial Handling Qualities Assessment," in *The Aeronautical Journal*, vol. 107, No. 1744, 2003, pp. 511–520.

[7] D.T. McRuer, E. S. Krendel, *Mathematical Models of Human Pilot Behavior*, AGARD AG-188, 1974.

[8] R. Szabolcsi, "Pilot-in-the-Loop Problem and its Solution, " *Review of the Air Force Academy*, No. 1, Brasov, Romania, 2009, pp. 12–22.

[9] J. Boril, K. Zaplatilek, R. Jalovecky, "Filter Optimization for Human - Machine Interaction in Aviation", IEEE/ASME International Conference on Advanced Intelligent Mechatronics 2013, submitted for publication.

[10] Ch.T. Chen, *Signals and Systems.* Oxford University Press, Third Edition, 2004.

[11] A. Gilat, V. Subramanian, *Numerical Methods for Engineers and Scientists. An introduction with Applications Using MATLAB®*. Wiley, Second Edition, 2010.

[12] J.B. Dabney, T.L. Harman, *Mastering Simulink®*. Pearson Prentice-Hall, Inc., 2004.

[13] K. Su, *Analog Filters.* Kluwer Academic Publishers, Second Edition, 2010.

[14] R. Schaumann, H. Xiao, M. Van Valkenburg, *Design of Analog Filters.* Oxford University Press, Second Edition, 2009.

[15] S. Winder, *Analog and Digital Filter Design.* Elsevier Science, Second Edition, 2002.

[16] D. Hanselman, B. Littlefield, *Mastering MATLAB® 7.* Pearson Prentice-Hall, Inc., 2005.

[17] K. Klee, R. Allen, *Simulation of Dynamic Systems with MATLAB® and Simulink®*. CRC Press, Second Edition, 2011.

[18] http://www.spectrum-soft.com, verified on February 2013.