Filter optimization and sensitivity analysis of pilot behavior tested on flight simulator

Jan Boril, Karel Zaplatilek and Rudolf Jalovecky

Abstract— This paper describes another option for the evaluation and analysis of data measured on flight simulator using alternative human behavior models – human as a pilot while flying an aircraft. The measured data was then mathematically analyzed in the MATLAB® environment, providing the input and output data for the filter optimization. Paper also describes the original method of mathematical human behavior model sensitivity analysis, or more precisely, pilot's response to a sudden change of flight altitude. The model is in the form of a rational fraction function of 2nd order and is used for all practical experiments. Individual coefficients of the transfer function represent the pilot's ability to fly the aircraft, i.e. all the coefficients have a specific and practical meaning. The main aim of this paper is optimal filter design with obtaining the best transfer function parameters and analyzing relative sensitivities of all the transfer function coefficients of the pilot's behavior model. Another aim of this paper is to determine coefficient ranges of the pilot's behavior model for further practical use. Due to the measurements, filter optimization and sensitivity analysis the pilot behavior model can obtain more realistic shape useful in the aircraft's flight control systems at an early stage of its development.

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

I. INTRODUCTION

IN today's automated and digital world the focus is placed on the development of computers and artificial intelligence. However, a pilot or an operator is an essential part of any aircraft flight control. Only time will tell if a pilot (operator) can be fully replaced by a computer or artificial intelligence. That's why aircraft manufacturers keep conducting research into the influence of human factors.

The pilot is the most important part of the aircraft control systems. That still applies even nowadays when aircraft are equipped with modern control systems for maneuvering and controlling individual flight parameters. These systems are controlled by digital computers. If one of these automated systems fails, the pilot must be able to take over the aircraft controls - that means he must be able to fly the aircraft and land it safely. The automation of some phases of flight resulted in the production of semi-automated flight control systems. These semi-automated systems make the pilot's flight much easier. The systems are guiding the pilot through the correct procedures and maneuvers via multifunction displays installed in cockpits [1].

The theory of automated flight control systems use states that the pilot watches many flight parameters when carrying out difficult and complex tasks such as for example landing. The pilot is trying to keep these flight parameters (altitude, vertical speed, runway distance, etc.) within a certain range. This is intensive and short overload and can have a negative effect in emergency situations. The pilot's response time prolongs and due to the stress and psychological overload the pilot makes consequent mistakes. Aircraft crash statistics show that the probability of aircraft accident increases exactly when carrying out these tasks.

How would the pilot react in an unpredictable flight situation if one of the automated systems cut off or if a sudden change of angles occurred due to bad weather conditions? Authors modeled the unpredictable flight situations on flight simulators. The results were then analyzed and evaluated in the MATLB® program. A pilot could be mathematically described by a transfer function. Modeling and simulations are the most effective tool for gaining the needed results, yet saving money, time and manpower [2]. Knowledge about the pilot's behavior is a very important aspect regarding flight safety [3].

II. THEORETICAL BACKGROUND OF THE PILOT BEHAVIOR MODEL

A pilot behavior model is an important aspect for the initial development and testing stages of aircraft flight characteristics. A mathematical pilot model [4] depends on:

- complexity of the controlled system,
- pilot's training level,
- his physical and psychological state and,
- last but not least, on the task the pilot is carrying out.

It is quite difficult to model pilot behavior using a mathematical model taking into consideration all the possible behavior conditions when there is no complete list of biological and physiological processes taking place in the human brain. Therefore, it is not possible to create a comprehensive list of functions describing human thinking

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process [5] from which all the pilot's actions in the pilot-aircraft system are derived.

When creating a mathematical model of pilot behavior it is necessary to also take into consideration differences between pilots of aircraft with fixed wings and pilots of helicopters. Each aircraft type has its own sophisticated control systems and each pilot needs appropriate training. The decision making process and selection of the response are, to a certain extent, individual especially in emergency situations. Human behavior has one disadvantage and that is repeatability of the maneuver [6]. If the pilot is trying to repeat the same maneuver twice, the final result will be two slightly different maneuvers. A mathematical model of human behavior eliminates this disadvantage. The transfer function describing the mathematical model of pilot behavior [5], [7] - [9], further used in this paper, and is described as follows:

$$F(s) = \frac{Y(s)}{X(s)} = K \frac{(T_3 s + 1)}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau s} \, . \qquad (1)$$

Where:

K - Pilot gain represents pilot habits for a given type of aircraft control. If the pilot over-reacts or if a change in system amplification occurs 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.

T_2 - Neuromuscular lag time constant represents the pilot´s delay in activity caused 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.

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. Estimating and predicting the future state is the ability to imagine the future steps and states of the surrounding area. The pilot obtains this 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. Increasing the value of transport delay may cause the regulatory system to become unstable [10].

This shape of transfer function is based on the assumption that the pilot is behaving in a linear manner, i.e. as a linear element. In a real regulation circuit there are always, up to a certain extent, non-linear elements, as it is in human-machine systems. The human operator's control action is not linear and is also influenced by negative aspects of non-linear elements such as hysteresis, insensitivity, saturation or non-linear variable amplification. It is challenging, not only to identify these elements but also to categorize or allocate them into a regulation circuit with multiple feedbacks. According to [5] there are many publications describing scientists assigning individual time constants to physiological processes. However, there are many opponents stating that this approach is not correct as neuro-motive functions and central nervous system functions are mixed together.

III. PILOT RESPONSE MEASURING PROCEDURE

The flight parameters and the generally measured values for analog filter optimization and sensitivity analysis were measured during a three-month exchange program at the University of Hertfordshire, Hatfield. The university has a laboratory with flight simulators used for pilot training as well as for research purposes. The mentioned flight simulator is primarily intended for pilot's preparation especially for training flight procedures before flight, during and after the flight.

The flight simulator Cessna 152 (Fig. 1) consists of a Cessna 152 aircraft fuselage with two seats for crew. This fuselage is anchored to a static base fixed to the floor. The flight simulation was done by three projectors, projecting images onto a parabolic wall. Based on the research needs software X-Plane 9 from Laminar Research Company was used. The main advantage of this software is its precise and detailed simulation of flight physics for all individual aircrafts. The simulator as a whole is controlled by a PC - also called an Instructor Station. An instructor sitting at this station can change any flight parameters during the flight simulation. All control elements, flight instruments and control stick inside the cockpit are connected to the instructor station. The pilot can fully focus on flying the plane while the instructor can see all the real time parameters on his monitor.

Fig. 1 Cessna 152 Cockpit Simulator (University of Hertfordshire)

One of the most important tasks regarding pilot actions, while flying an aircraft, is to watch a reference signal. Many flight tasks (i.e. semi-automated landing, airborne refueling, flight formation, etc.) require focus on accurate control based on watching important flight parameters while carrying out these tasks. That is why the input signal was defined for this study as a step change of altitude. The pilot had to respond to this step change and bring the plane back to its original altitude by deflecting only the aircraft elevator.

The individual tests were conducted as follows. The pilot maintained the plane at a straight horizontal flight. The instructor suddenly dropped the flight altitude by 100ft. The pilot's task was to bring the plane back to its original altitude as quickly as possible and stay there. To do so, the pilot could only use the aircraft elevator deflection. In real life, such a step change could be caused by severe weather conditions or turbulence. The input and output data were recorded in data tables and later analyzed.

Some limiting factors, occurring during testing, affected the measured results. Firstly, in real situation the pilot senses any aircraft change by his senses organs. This cannot be ensured when using a simulator fixed to the floor. The tested pilots only sensed the altitude change visually by watching the altimeter in the cockpit and by expecting a sudden change. This fact largely influenced (increased) the time constant of the pilot transport delay between sensory perception of the change and a brain response.

After result evaluation and consultation with the pilots about the flight process the pilots talked about greater control sensitivity of the simulator compared to a real aircraft. Another factor lowering the realistic feel of the flight was a small observation angle as seen in Fig. 1. Due to the distance and curvature of the screen used for image projecting the pilots didn't have 100% the same feeling as they would in a real aircraft cockpit.

IV. ANALOG FILTER OPTIMIZATION

As described before, the analog filter has five parameters for optimization. Four are the filter coefficients and the fifth one is a transport delay. Each parameter represents different pilot's physiological and psychological states.

There are five numerical parameters in an optimization process. That means that the optimization proceeds in five dimensional optimization space. The space can be defined by the formula:

$$Delta = f\,(T_1, T_2, T_3, K, \tau). \tag{2}$$

The optimization process looks for the minimum of the optimization space according to the following formula:

$$V_{optim} = \min(Delta), \tag{3}$$

where V_{optim} is a vector of optimal parameters. The formula (3) defines basic optimization strategy of the process. The results include all filter parameters with optimal values

$$V_{optim} = (T_{1optim}, T_{2optim}, T_{3optim}, K_{optim}, \tau_{optim}) \tag{4}$$

Most of the optimization methods work with a so-called objective function that is used for quality evaluation of the optimization process. In this case, the sum of the square of deviations is used [11], [12]. The objective function of the optimization process is calculated as follows:

$$Delta = \sum \left(f_{resp} - f_{out}\right)^2, \tag{5}$$

where f_{resp} is the filter response and f_{out} is the recorded pilot's response. The formula (5) is a typical optimization criterion in similar cases [11], [12]. The variable Delta is optimized to a minimum during the optimization process. The main objective of the optimization is to find the coefficients of the vector V_{optim}.

It is necessary to optimize the analog filter for individual personalization. The optimization steps are as follows:

- Download input data with particular pilot responses.
- Launch the optimization algorithm.
- Identify optimal filter coefficients.
- Evaluate the pilot's personal features.

The block diagram of the optimization process is shown in Fig. 2. The algorithm was developed in the MATLAB environment [13].

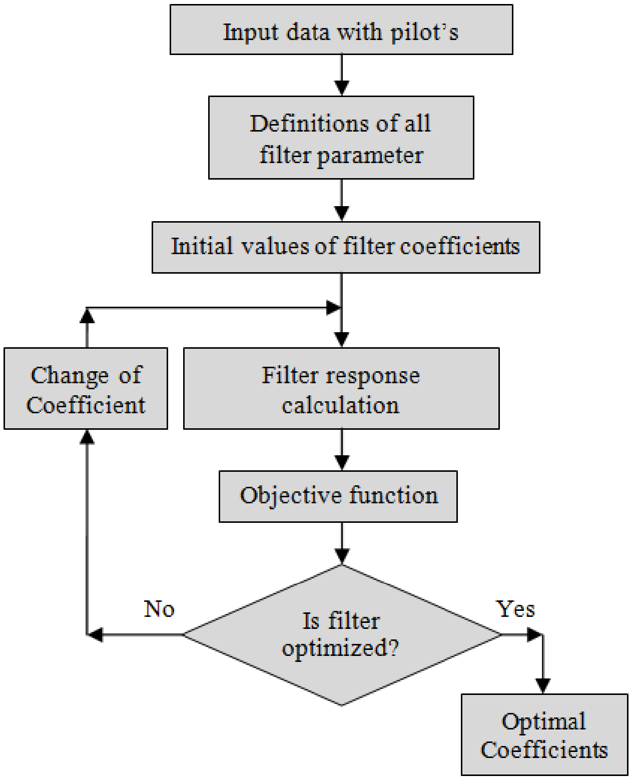


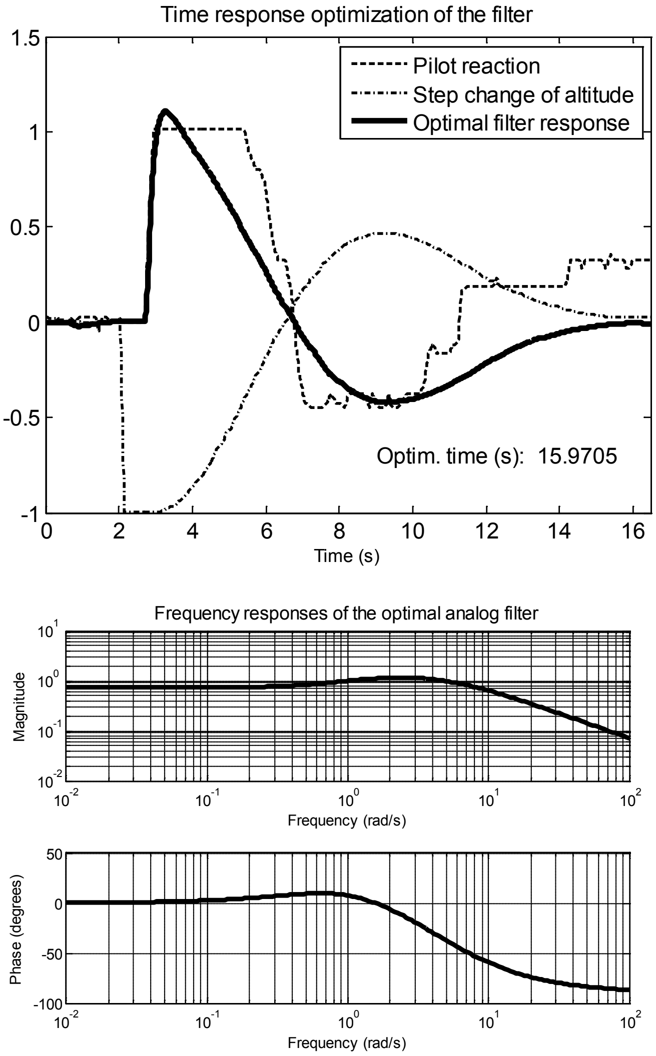
Fig. 2. Block diagram of the optimization algorithm

The optimization algorithm is a so-called single-pass iterative technique without penalization [14]. The algorithm can have either a firm step or a variable step within the filter coefficients optimization. The optimal values of the filter coefficients are the output of the algorithm including their optimal intervals and transport delay.

The results of filter optimization are shown in Fig. 3, they include the time responses, the optimal filter coefficients and the frequency responses. The filter coefficients are written in two forms: as second-order section coefficients (ωr, Q) and as the pilot constants (T_1, T_2, T_3, K, τ).

It is clear from the optimization results that the optimal filter has a relatively low quality factor and a low angular frequency. The optimal filter is an analog electronic system working in so-called aperiodic mode [14]. Its optimal coefficients depend on a particular pilot response.

When the optimization process is evaluated it is suitable to draw an optimization trajectory that shows optimization rate. A typical optimization trajectory is shown in Fig. 4. In addition, a different diagram can be drawn using a polar graph, see Fig. 5.



$$\omega_{roptim} = 2{,}673\, s^{-1},\ Q_{optim} = 0{,}416\,(-).$$

$$T_{1optim} = 0{,}700\, s,\ T_{2optim} = 0{,}200\, s,$$

$$T_{3optim} = 1{,}367\, s,\ K_{optim} = 0{,}733\,(-),\ \tau_{optim} = 0{,}667\, s.$$

Fig. 3. Block diagram of the optimization algorithm.

The spiral in Fig. 5 shows the route to the optimum. The distance from the center of the circle determines the optimization quality. Ideally, this value should be zero. The number of points in Fig. 5 matches the number of iterations. This analysis method is very suitable for further result comparison or trend analysis [11]. Based on a lot of practical experiments, it is possible to say that the polar space is a more comfortable way of presenting the optimization results.

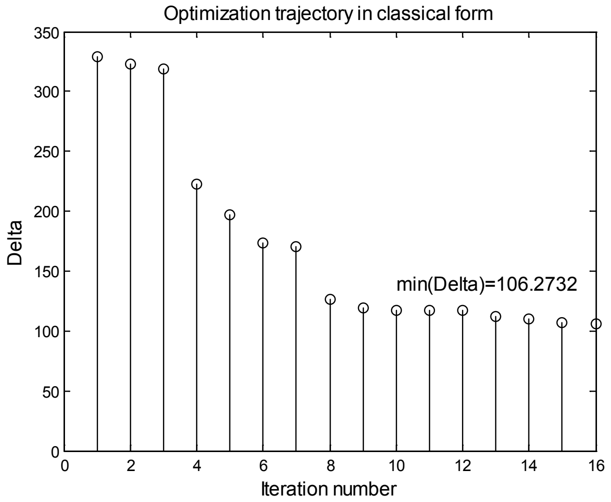


Fig. 4. Optimization trajectory using the stem command in MATLAB.

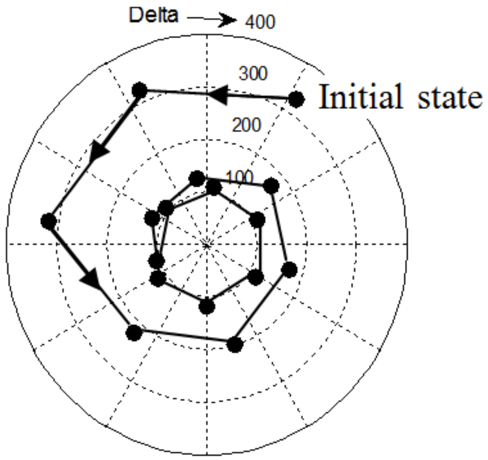


Fig. 5. Optimization trajectory in polar coordinates.

V. SENSITIVITY ANALYSIS OF FILTER TIME-RESPONSE SOLUTION

Based on the pilot's response to the flight altitude change a mathematical model is created (1). The first task is to optimize the model so that it best reflects the pilot's response. The optimization should:

- Determine ideal constants K, T_1, T_2 a T_3.
- Determine its time response.

After the optimal constants are known from equation (1), a sensitivity analysis needs to be done. Based on the analysis, the mathematical model of pilot response (1) is an analogue filter of 2nd order with non-standard numerator of its transfer function [15]. Due to the physiological and biological meaning of the equation coefficients (1) it is unsuitable to conduct standard analysis of relative filter sensitivities [15], [16]. The user does not need to know the sensitivity values of the limit circular frequencies and the quality numerator. The user needs to know global sensitivity of the time response to changes of individual constants. The knowledge of these sensitivities can be beneficial for evaluation of the pilot response model characteristics. As far as we are aware no such sensitivity analysis has yet been published as.

Fig. 6 shows a general diagram of the whole analysis process and the filter optimization. This chapter describes analysis of relative sensitivities of the depicted blocks.

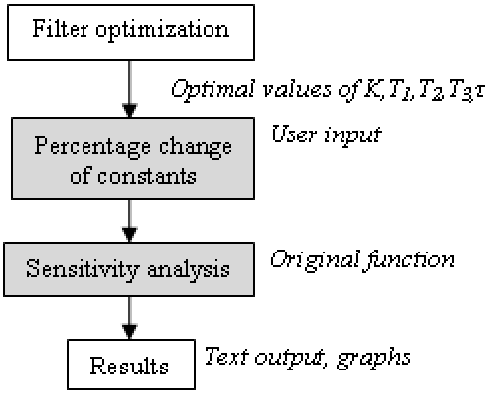


Fig. 6. General block diagram of filter optimization and analysis.

The entire sensitivity analysis process is shown in Fig. 7 with constant K as an example. An optimal value of the constant K is selected as the initial value of the constant which is one of the outputs of the optimization algorithm. Next, the filter time response is calculated using linear convolution. The recordings of altitude flight changes are used as the input signal - see below. The constant K is then being swept around its optimal value according to the users' needs. The cycle is finished after calculation and depiction of a defined number of curves

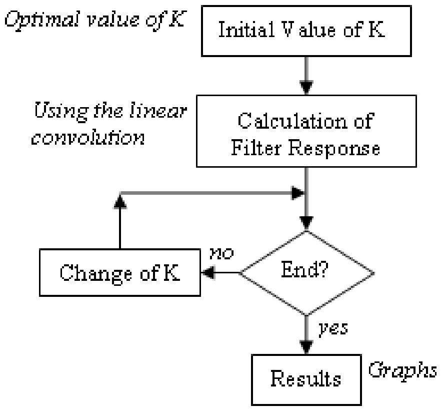
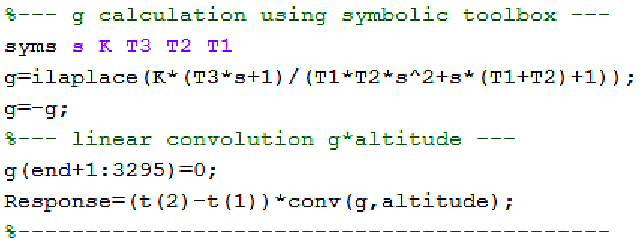


Fig. 7. Sensitivity analysis of the constant K.

In order to calculate and depict the time flow of the filter response, its impulse response needed to be identified. An established procedure was used utilizing symbolic Maths in the MATLAB environment as shown in Fig. 8.



```
%--- g calculation using symbolic toolbox ---
syms s K T3 T2 T1
g=ilaplace(K*(T3*s+1)/(T1*T2*s^2+s*(T1+T2)+1));
g=-g;
%--- linear convolution g*altitude ---
g(end+1:3295)=0;
Response=(t(2)-t(1))*conv(g,altitude);
%-------------------------------------------
```

Fig. 8. Calculation of the filter impulse and time responses.

An impulse response in a symbolic form was calculated using the ilaplace function, which is a part of the Symbolic Maths Toolbox^{TM}. The filter transfer function was used as the input parameter (1) without transport delay. The change of sign of impulse response is one of the first points of this paper. Taking into consideration the inversion character of the pilot's response, it was necessary to modify the designed model (1) by inversion coefficient.

Then a filter time response is calculated using the internal function conv. A standard algorithm of linear convolution in the MATLAB system was used [17] - [19]. The subtraction of $t_{(2)}$-$t_{(1)}$ defines the sampling period.

Based on the above described principles, many other experiments were conducted with pilots and all the responses recorded. Fig. 9 shows typical a record of flight altitude changes (top graph) and pilot response (bottom dash-and – dotted line). The bold line in the bottom graph is the resultant calculation of the filter time response with optimal constant values according to (1).

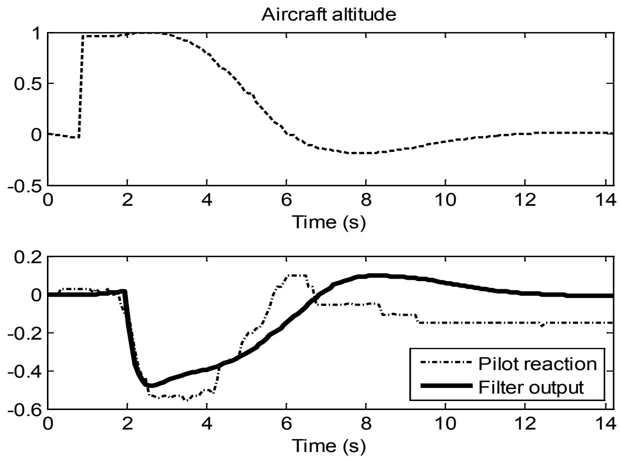


Fig. 9. Optimal approximation of pilot response to change of altitude.

Response time flows were calculated and depicted according to Fig. 6 and Fig. 7 using constant value changes. Fig. 10 shows the results of filter response sensitivity analysis for constants K a T_1. Both constants were changed by a maximum of 5 %.

The acronym MRC stands for Maximum Relative Change of the constants. It is clear that none of the constants could cause a change bigger than the 5%. Similar results are achieved for constants T_2 a T_3 and are shown in Fig. 11, having the same input conditions. The changes are of the same order.

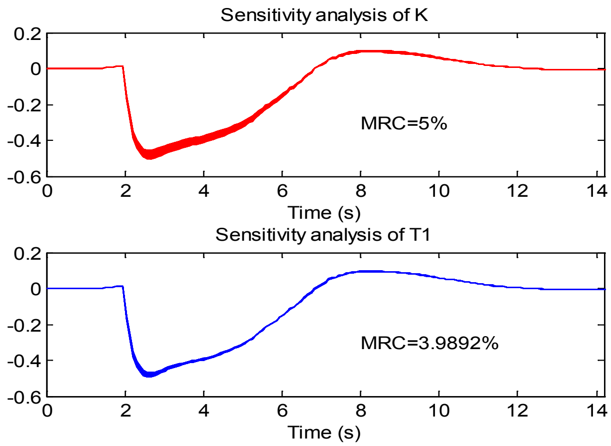


Fig. 10. Sensitivity analysis of the constants K and T_1

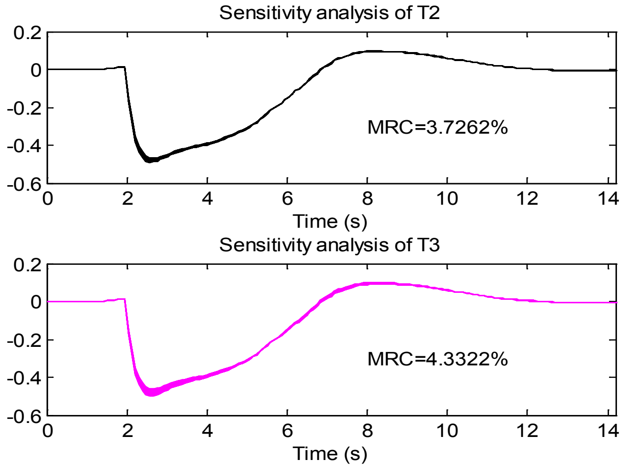


Fig. 11. Sensitivity analysis of the constants T_2 and T_3.

For better visual evaluation an absolute error of all four relative sensitivities was calculated from the equation:

$$AE = \delta_{K\max} - 5\% \quad (\%), \tag{6}$$

AE means Absolute Error and   is the maximum relative error or constant K. Fig. 12 shows clearly all four absolute errors. Fig. 13 shows text output of the MATLAB application for sensitivity calculations.

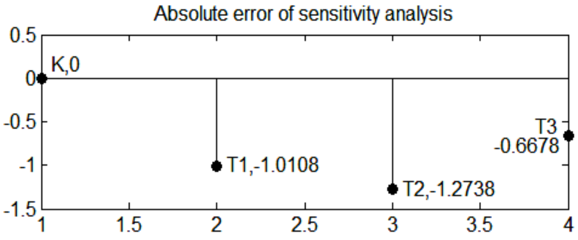
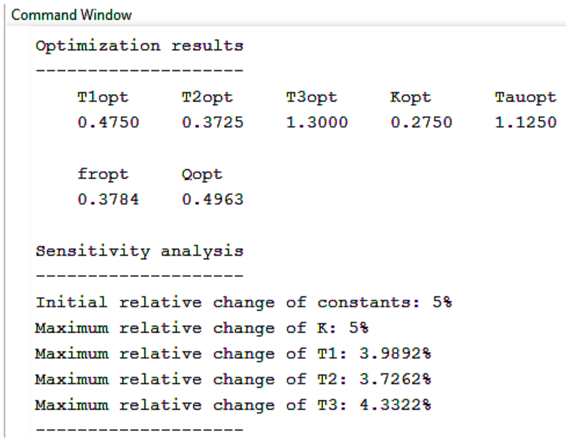


Fig. 12. Sensitivity analysis results comparison.

Fig. 13 clearly shows the reason for low sensitivity of all constants. The analogue filter as a mathematical model has a very low limit frequency, especially a low quality coefficient, having. The filter is then a linear system, working in aperiodic mode [17], [18]. In conclusion, it is possible to say that the tested model is a stable model and regarding response relative sensitivities its sensitivity is low. That is good news for further applications and further expansion of this model.



```
Optimization results
--------------------
    T1opt      T2opt      T3opt      Kopt       Tauopt
    0.4750     0.3725     1.3000     0.2750     1.1250

    fropt      Qopt
    0.3784     0.4963

Sensitivity analysis
--------------------
Initial relative change of constants: 5%
Maximum relative change of K: 5%
Maximum relative change of T1: 3.9892%
Maximum relative change of T2: 3.7262%
Maximum relative change of T3: 4.3322%
--------------------
```

Fig. 13. Example of MATLAB application text output.

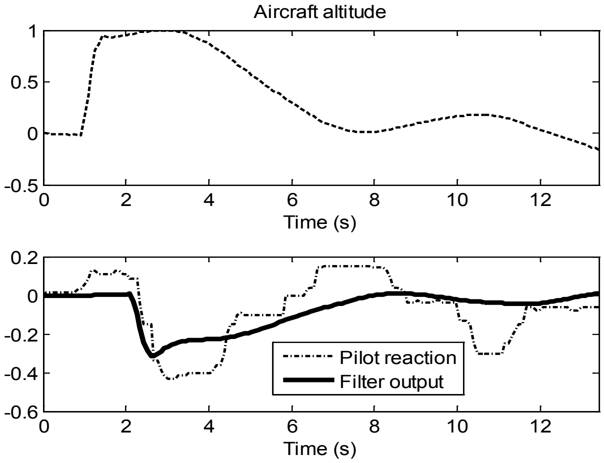


Fig. 14. Optimal approximation of another pilot reaction.

For more information, Fig. 14 shows response of another pilot to the altitude change. Fig. 15 shows sensitivity analysis for constant T_2 a T_3.

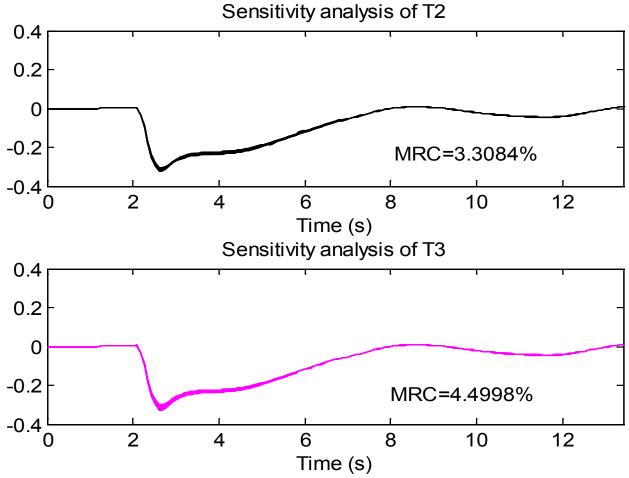


Fig. 15. Alternate sensitivity analysis of the constants T_2 and T_3.

As mentioned above and based on inversion pilot behavior when the aircraft altitude was changed, the hereby used filter transfer function was modified by -1 coefficient. The final modified model then looks as follows

$$F(s)=\frac{Y(s)}{X(s)}=-K\frac{(T_3 s+1)}{(T_1 s+1)(T_2 s+1)}e^{-\tau s}\ . \qquad (7)$$

It is also necessary to mention that even if the tested model is relatively simple regarding its analysis; its optimization was quite difficult and complex. It is 5D optimization of constants according to.

VI. DETERMINATION OF TIME CONSTANT RANGE FOR PILOT BEHAVIOR MODEL

5 step changes of flight altitude were selected, from all data measured on the flight simulator, for further analysis. These 5 changes were tested on 5 different pilots. Only the most significant time flows were selected to determine time constant range and pilot gain. As the length of this paper is limited, not all 5 time flows are presented here. The time flows of pilot 1 (Fig. 9) and a pilot 2 (Fig. 14) are presented in section V.

The results of optimal constant values are clearly shown in Tab.1. It is clear that each pilot responded in a different way. Each of them chose the best tactic to their best knowledge to compensate for the flight altitude step change of 100ft. As the sensitivity of the flight simulator controls was quite high, some altitude overshoots accrued when pilots compensated for the step change. Time constant ranges and amplification are:

- T_1 = 0.4318 ÷ 0.7000 (s),
- T_2 = 0.2000 ÷ 0.7000 (s),
- T_3 = 1.3670 ÷ 5.1955 (s),
- τ = 0.6670 ÷ 1.1818 (s),
- K = 0.1000 ÷ 0.7330 (-).

The predictive time constant T_3, reflecting the pilot's experience to predict a future flight input, has quite a wide range. This level of wide range represents the highest level of situation awareness at which the pilot gained such knowledge about the state and dynamics of the individual system elements that he was able, not only to comprehend the current situation, but also to apprehend future situation developments. This means that each pilot's intervention into the control system is equal to his experience and intuition. Thus, wide ranges of Lead Time Constants for differently trained pilots are presented.

It is also interesting to see the high values of Transport Delay. Scientists put this down to the fact that the pilots were sensing the change only visually. They were watching the altimeter in a cockpit and expecting an altitude change. The simulator is not equipped with movable base that would provide the authenticity of real flight. The pilots were not sensing the altitude change with their body, but responded only to the visual perception. This is the reason why their responses took longer than expected.

Table 1. Optimal Constant Values For 5 Practical Tests

Pilot	**T_1 (s)**	**T_2 (s)**	**T_3 (s)**	**τ (s)**	**K (-)**
1.	0.4318	0.4545	1.9773	1.0909	0.2136
2.	0.5136	0.5091	4.9273	1.1818	0.1000
3.	0.6500	0.7000	5.1955	0.9545	0.1000
4.	0.5136	0.5364	3.5864	1.0909	0.1000
5.	0.7000	0.2000	1.3670	0.6670	0.7330

The authors of this paper have constructed an experimental workplace with a flight simulator at the Department of Aerospace Electrical Systems, see Fig. 16. Testing of future military pilots will take place there, focusing on precise determination of time constant range of pilot behavior.

Fig. 16. Aircraft simulator (Department of Aerospace Electrical Systems, Univeristy of Defence).

VII. CONCLUSION

Testing of pilots on a flight simulator, or rather, pilot's responses to an unpredicted step change of flight altitude has been verified and approaches for modeling and pilot behavior simulation have been extended.

The analog second-order filter was used as a simple model of a pilot’s response. The filter was optimized using a typical iterative algorithm developed in the MATLAB environment. All of the filter coefficients have a specific meaning corresponding to the pilot’s physical and psychological states. The main aim of the optimization was to find an optimal analog filter working as a pilot’s response model.

An original method of sensitivity analysis of transfer function of 2nd order was described. The analysis was based on a defined change of model coefficients. Particular values of these coefficients were taken from the original optimization algorithm. Many practical experiments uncovered that the given mathematical model had very low sensitivity which is good for its future potential utilization. What’s more, the range of real model coefficients was determined by these tests. Despite the relatively low number of practical tests, the first results showed the main trends in range identification.

A mathematical model of a higher order was also experimentally tested for possible use. It verified better approximation of pilot response. The main task of these experiments is to identify the biological and physiological meanings of these coefficients in an aircraft control system. For these tasks medical staff will have to involve.

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