Identification of Human Operator Model Parameters in System with Saturated Actuator ⋆

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Abstract: In this paper, the closed-loop human-machine system is studied under the framework of the control systems theory. The human operator model is considered concerning the human's ability for adaptation to the current operational conditions. For flying vehicles this property corresponds the crossover model by McRuer. In the paper, the actuator is modeled in the form of a first-order low-pass filter with the saturation. The paper deals with the case when the human operator manually controls the vehicle along one angular coordinate. In the paper, an algorithm for identifying the parameters of a human operator in a nonlinear control system is proposed. The implementation of the algorithm is based on solving a nonlinear optimization problem with restrictions on frequency characteristics, the range of possible values of the operator's model, and performance criteria for controlling a closed man-machine system. The proposed algorithm is illustrated by a numerical example, for which the human model parameters values are found by the example of the unmanned aerial vehicle's human control. For comparison, the parameters of the human operator model for a linear system are given.

Keywords: human-machine system, modeling, identification, optimization, nonlinear systems

1. INTRODUCTION

The increasing complexity of modern technologies and problems of aircraft control does not exclude a human from the system, but, on the contrary, often requires its closer participation in control processes. At the same time, this method increases the operator's workload and reduces the efficiency of the Human-Machine Control System (MMCS). One of the way to solve this problem is to transfer some of the operator's functions to intelligent cybernetic systems, but due to the low reliability and high cost of such systems, in some situations, ergonomic means, onboard digital computers and adaptive control algorithms are used in fly-by-wire systems. Due to the complexity of the pilot-aircraft control systems, much of the experimental and theoretical research has been devoted to this goal, including the study of manual aircraft control. The present paper is based on advances in aircraft systems design and the study of aircraft piloted control systems.

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A human, being a part of a control loop, behaves like a controller and influences on the stability and quality of the system. The proposed software is a utility to carry out an intensive computer simulation of the HMS to avoid errors and malfunctions in the system operation due to the human factor. It is especially actual for systems with high safety requirements, for example, for piloted aircraft. In those areas of aviation, where possible, simulation modeling is successfully already used, see (Font et al., 2010; Somov et al., 2013; Jaiswal et al., 2021). For its implementation, algorithms for the numerical solution of differential equations are being developed. The mathematical description of the human operator (HO) is usually a nontrivial problem due to the complexity of his behavior. Most of the papers devoted to the dynamics descriptions and calculating parameters of HO models are based on experimental data. The input signal of the system is considered as a random stationary function of time, and the process is characterized as a stationary one. Based on the experimental data, the frequency response is calculated using spectral analysis methods, see (Tse and Weinert, 1975). In this regard, the identification problem of the HO model parameters by computer modeling before the real-world testing on the actual equipment is relevant.

As a control component, the HO demonstrates a complex combination of nonlinear and time-varying behavior. This fact does not allow one to describe it with a single universal model. Therefore, its actions are divided into tasks, for each of which assumptions about its behavior are introduced. There is a widespread assumption that a trained HO in demand control tasks acts as an optimal regulator, see McRuer (1980). Thus, it is supposed that the HO minimizes the cost function, see (Phatak et al., 1976): $J = E\left[\int_0^T (qe^2 + gu^2)\, dt\right]$, where e is the control error, u is the controlling input, q and g are the cost function weightings.

Thus, a method for determining the HO model parameters based on the criterion of the minimum root-mean-square error is used, see (Aizerman and Freeman, 1963). The weights of the cost function can be, for example, the desired time of the transients, cf. (Phatak et al., 1976) or the criterion of requirements for the control quality, cf. (Tran et al., 2017). In papers where the weight coefficients characterize the control tasks requirements and the constraints imposed on them, the authors note the difficulty of their choice, see (Kleinman et al., 1970; Phatak and Kessler, 1977). Kuznetsov (2020) recently presented a survey, where well-known theoretical and engineering problems in which hidden oscillations play an important role. Particularly, oscillations of this kind may appear in flight control systems due to control input limitations, cf. (Leonov et al., 2012; Andrievsky et al., 2018a,b, 2019).

It is worth mentioning, that the formulation of the parameter identification problem only from this view does not consider the physical capabilities of the HO. Also, this approach is suitable for linear systems, which rarely occur in real engineering. Thus, the purpose of this paper is to develop an approach for identifying HO model parameters in the nonlinear system, taking into account the adaptability of the HO to the task variables, which maximally reflects the properties of the HO behavior in control.

The rest of the paper is organized as follows. The human-machine system model is described in Sec. 2. The algorithm of human operator parameters identification is presented in Sec. 3. The simulation results are described in Sec. 4. Concluding remarks are given in Sec. 5.

2. HUMAN-MACHINE SYSTEM MODEL

The property of HO adaptation to the plant dynamics and the input signal spectrum width revealed from the full-scale tests makes it possible to consider the human-machine systems (HMS) characteristics remain sufficiently constant. In this case, the maximum cutoff frequency provided by the HO depends to a greater extent on the type of transfer function of the plant and a lesser extent on the frequency band of the input signal. A trained or experienced HO who knows his characteristics and system dynamics will perform optimally by giving control signals in the best way. The following data were obtained from experiments: neuromuscular lag of a human's reaction, the degree of training, and the preview time. The property of the HO adaptability to task variables allows him to equalize the rest of the parameters of his model, see (McRuer, 1980; McRuer and Krendel, 1974; Pool et al., 2009).

2.1 Model of a Human Operator

The methods of automated control theory can be used to design a mathematical model of the HO behavior in continuous systems. Examples of such systems are vehicles, tracking or guidance tasks, automated parameter control systems. Within the framework of the structural approach, the HO model is presented in the form of a model of perception of visual information and its elementary correction, additional correction when choosing a control strategy, and working out commands by the neuromuscular system. In this study, the compensatory HMS model with preview is used, which considers the control error and the future change of the controlled parameter, see (Reid and Drewell, 1972; Efremov et al., 2019). Such a model is suitable for describing the remote control system of a unmanned aerial vehicle and a wheeled vehicle when the HO turns the rudder in advance by his experience. Then the HO model controlling the angular position relative to the transverse axis of the plant will be written in the following form, see (McRuer, 1980; Reid and Drewell, 1972):

$$W_{\theta^*}^{\theta}(s) = \frac{W_1(s) + 1}{1/W_2(s) + 1}, \tag{1}$$

where where θ^*, θ are the reference signal and actual output, $W_1(s)$ and $W_2(s)$ the following transfer functions:

$$W_1(s) = \frac{s}{T_1 s + 1}, \tag{2}$$

$$W_2(s) = \frac{K_2(T_2 s + 1)}{(T_3 s + 1)} \cdot \exp(-\tau s), \tag{3}$$

where T_1 is the time of preview, τ is the HO's neuromuscular time constant. Parameters T_1 and τ are time-invariant and their values are 0.2 s. The transfer function from control error to HO input $W_2(s)$ is a McRuer model that fairly close describes human behavior in the cutoff frequency range, see (McRuer and Krendel, 1974). HO equalizes the gain K_2 and the time constants T_2 and T_3 depending on the task variables. Note that, in general, the form of the HO model depends on the plant dynamics. Some of these correlations obtained experimentally are presented in (McRuer and Krendel, 1974).

2.2 Model of a Controlled Machine

The linear part of the control actuator model can be represented as a lag element of the first or second order. The nonlinear effects of actuator rate limit can be described by the following odd-symmetric function

$$\mathrm{sat}(b) = \begin{cases} B \cdot \mathrm{sign}(b) & \text{if } |b| > B, \\ b, & \text{otherwice,} \end{cases} \tag{4}$$

where B is the limit of the function value in magnitude.

Machine motion can be described by the Euler–Lagrange equations. So, for many plants of mechanics, such as servo motors of manipulators, aircraft, vessels, it will be of the same type and differ only in parameters. These plants can modeled with sufficient accuracy by the following transfer function from the HO input to the system output, see (Aizerman and Freeman, 1963):

$$W_{u_o}^{\theta}(s) = \frac{K_a}{(T_a s + 1)} \cdot \frac{K(Ts + 1)}{s(T_o^2 s^2 + 2T_o \xi s + 1)}, \tag{5}$$

where u_o is HO control signal, K_a and T_a are the gain and the time lag of the actuator, K, T, T_o are the gain and the time lead and lag constants of the plant, ξ denotes the plant damping ratio.

2.3 The Nonlinear Correction Method

It is well known through many publications that actuator nonlinearities can degrade the system performance. It can lead to undesired oscillations, to loss of system stability and controllability, see (Klyde and Mitchell, 2004; Hippe, 2006). The results of studies of such systems have shown the existence of limit cycles and hidden oscillations, see (Mehra and Prasanth, 1998; Andrievsky et al., 2016). To expand the stability area, prevent self-oscillations, improve the quality and accuracy of control processes in automatic control systems, the method of nonlinear correction is used, see (Sharov and Sharov, 1974; Filatov and Sharov, 1977). It is based on the introduction of a nonlinear four-port network into the system. The successful application of the correction method is shown not in papers devoted to electric drive control, cf. (Skorospeshkin et al., 2015), and also in manual control of an aircraft (Andrievsky et al., 2015; Zaitceva, 2019). A kind of such device is pseudo-linear two-port networks, which are serially introduced into the actuator control loop to compensate for the negative phase shift between the input and output signals. Their two-channel structure makes it possible to achieve the property of independence of the amplitude and phase-frequency responses, which opens up the possibility of supplying a wide range of input signals of a nonlinear system. In this work, it is proposed to use a correcting device described by the following equations:

$$\begin{aligned} u_1 &= |u|, \\ u_2 &= \text{sign}(z), \\ z &= W_{ph}(s)u, \\ u_3 &= |W_{dif}(s)\delta|, \\ y &= u_1 u_2 u_3 + u(1-u_3), \end{aligned} \tag{6}$$

where u and y are the input and output of correcting device, u_1, u_2, u_3 are the signal in the first, the second, and the third branch of the device respectively, δ is the angle of actuator deflection, the W_{ph} and W_{dif} are the transfer functions of the filters, described as follows:

$$\begin{aligned} W_{ph}(s) &= \frac{\tau_2 s + 1}{\tau_1 s + 1}, \\ W_{dif}(s) &= \frac{s}{\tau_3 s + 1}, \end{aligned} \tag{7}$$

where τ_1, τ_2, τ_3 are the time constants. Parameters τ_1 and τ_2 allows to adjustment of the shift phase value, the maximum of which falls in the frequency range 1–3 rad/s. Mathematical operations as module and signatures, located in separate channels of the device, make it possible to form the desired amplitude and phase of the signal independently. The frequency properties of the correcting device change depending on the δ as follows: the closer the δ is to the limit value, the stronger the positive phase shift. If the values are far from limiting, the device passes the signal without changing the phase.

3. ALGORITHM FOR PARAMETERS IDENTIFICATION OF THE HUMAN OPERATOR MODEL

This section briefly justifies and describes an algorithm for identifying the parameters of a HO model. The property of adaptation means that the HO aims to ensure the cutoff frequency of the open-loop system, corresponding to the optimal human-machine closed-loop system, see (McRuer, 1980). The crossover frequency of an open-loop system changes slightly for a chosen plant. Therefore, the HO equalizes the values of its dynamic parameters when the input signal bandwidth changes.

The most convenient way to assess the system optimality is such tools as oscillation index. It allows the determination of the system stability margin to the fullest extent possible, see (Aizerman and Freeman, 1963). The oscillation index fits into a narrow interval $[1.1, 1.6]$ for a broad class of optimal systems. In this case, the speed of response is approximately equal to the inversely proportional cutoff frequency of the open-loop system.

Another problem that needs to be considered is the correspondence of the HO model parameters to its physiological capabilities. At the moment, for a quantitative assessment of the quality of controllability for aviation technology, flight characteristics are used, see (Hess, 2016; Chetty and Lakshmi, 1991). The studies show that it can be successfully applied in other areas, for example, when a person controls a bicycle, see (Hess et al., 2012). According to these estimates, the control plant is perceived by the HO favorably if the parameters T_2, T_3 do not exceed the value equal to one. An increase in these parameters indicates an increasing complexity of the control process when the HO has to use forcing and delay. The gain K_2 has its optimum corresponding to the control task and the transfer factor of the controlled plant. The value of K_2 is selected so that the product $K_2 \cdot K$ is in the range of 5 to 9, see (McRuer and Krendel, 1974).

Based on the above, the parameters of the HO model can be found as a result of solving the optimization problem:

$$\begin{aligned} &\max\ J = \omega_c \\ &\text{subject to} \begin{cases} 0 < T_2, \\ T_3 \leq 1 \quad [\text{s}], \\ H_\infty \leq 1.25, \\ \eta > 0, \end{cases} \end{aligned} \tag{8}$$

where ω_c is the cutoff frequency of the open-loop system, H_∞ denotes the H-infinity gain (the oscillation index) of the closed-loop system, η is the degree of the closed-loop system stability found based on the eigenvalues of the closed-loop system transfer function $\Phi(s)$. The value of H_∞ is found by means of the standard MATLAB routine *norm(*Φ*,inf)*, applied to the closed-loop system transfer function $\Phi(s)$. Condition $\eta > 0$ means that all the poles of transfer function $\Phi(s)$ have negative real parts.

Thus, for a nonlinear system, the following algorithm for identifying the parameters of the HO model is proposed: *Algorithm 1.*

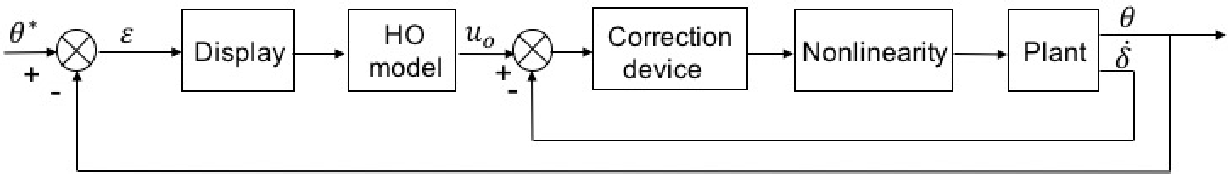

Fig. 1. The block diagram of the human-machine system model

(1) Choose the initial values of parameters K_2, T_2, T_3. Make a control loop consisting of models (1), (4), (5), (6) and feedbacks.
(2) Activate nonlinearity in the control loop, enter numerical values of saturation limit.
(3) Find the parameters τ_1, τ_2 of the filter (7) so that the system has optimal characteristics.
(4) Solve the optimization problem (8).

After the algorithm implementation, it is possible to assess the system performance, taking into account the parameters of the HO model by the frequency response and transients.

Computer algorithm implementation is possible in various ways. Despite this, there are general notes to its performance. First of all, the pure time delay link raises the order of the system to infinity, so it should be approximated as the Padé series in the form of the ratio of two polynomials of finite order, see (Brezenski, 1996). Second, the model of the correcting device (6) should be presented as a describing function. It can be done by the method of harmonic linearization, (Aizerman and Freeman, 1963). The τ_1 and τ_2 are chosen so that the stability margins in the vicinity of the crossover frequency corresponding to the optimal ones for a wide range of input signal amplitudes. Third, the cost function (8) is difficult to express analytically, so we used the capabilities of the numerical approaches of the MATLAB software. MATLAB incorporates the standard *fminsearch* local minimum search function, which returns a value using the Nelder-Mead algorithm, see (Nelder and Mead, 1965). The accuracy of this algorithm depends on the choice of the initial model parameters values. The initial parameters should not differ much from the optimal ones.

4. SIMULATION RESULTS

The simulated HMS model is shown in Fig. 3. In this model, an internal speed feedback loop is introduced. The following linear system parameters were chosen for computer simulation: the initial HO model parameters $K_{02} = 0.95$ s, $T_{02} = 0.05$ s, $T_{03} = 0.002$ s, $T_1 = 0.05$ s, $\tau_0 = 0.3$ s. The following nonlinear system parameters were chosen for computer simulation: the initial HO model parameters $K_{02} = 1.75$ s, $T_{02} = 0.5$ s, $T_{03} = 0.5$ s, $T_1 = 0.05$ s, $\tau_0 = 0.2$ s, parameters of the nonlinear filter $\tau_1 = 0.008$ s, $\tau_2 = 2.5$ s, $\tau_3 = 0.05$ s, the plant parameters $T_a = 0.076$ s, $K_a = 1$, $K = 130$, $T = 0.23$ s, $T_0 = 0.04$ s, $\xi = 3.6$, saturation rate limit is equal to 6 rad/s. For simplicity, let's set the display transfer function equal to one.

Table 1 presents the list of the system model parameters obtained as a result of the *Algorithm 1* implementation.

Table 1. System model parameters

Parameters	K_2	T_2	T_3	τ	ω_c	M	η
Linear system	0.53	0.002	0.064	0.32	6	1.248	1.6
Nonlinear system	0.6	0.6	0.5	0.18	1.64	1.249	2.26

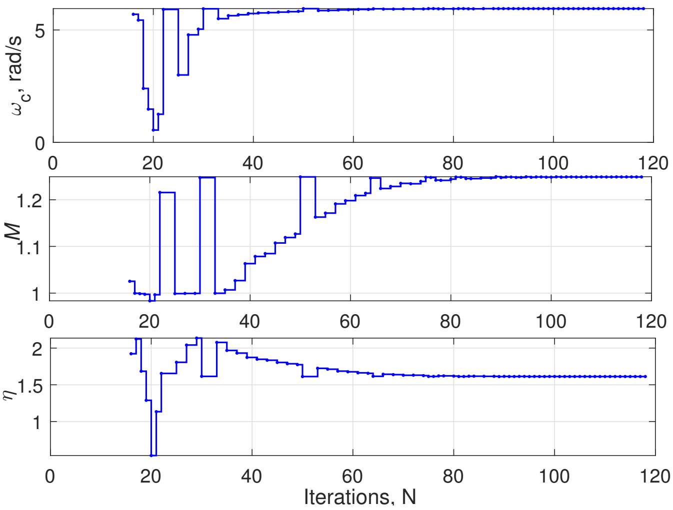

Fig. 2. Variation of the system parameters during optimization process

Also, the parameters for a linear system without saturation are given.

In the case of the simple operator action, $T_2 = T_3 = 0$ can be taken, which means that the operator produces a control action with proportional gain K_2 and a certain delay τ. The product $K_2 \cdot K = 65$ does not fit into the optimum values and indicates that the HO produces a control signal in an ultra low-frequency range. An increase in the parameters T_2 and T_3 in the nonlinear system shows an increase in the control complexity compared with the simple proportional control. It is seen from the fact that the operator introduces lead T_2 while filtering the high-frequency components of the movement by introducing lag T_3. Note that the parameters of the human operator model for the linear system from Tab. 1 are very close to the results of flight experiments from Mandal and Gu (2016), which confirms the validity of the proposed *Algorithm 1* and calculations.

To find the extremum for (8), $N = 188$ iterations of the algorithm were performed. Figure 2 shows how the value of Q varies depending on the iteration number N. The restrictions imposed in (8) begin to be fulfilled from the 23-rd iteration. Also, this figure shows that the number of iterations can be limited to 100 for speeding up getting the result.

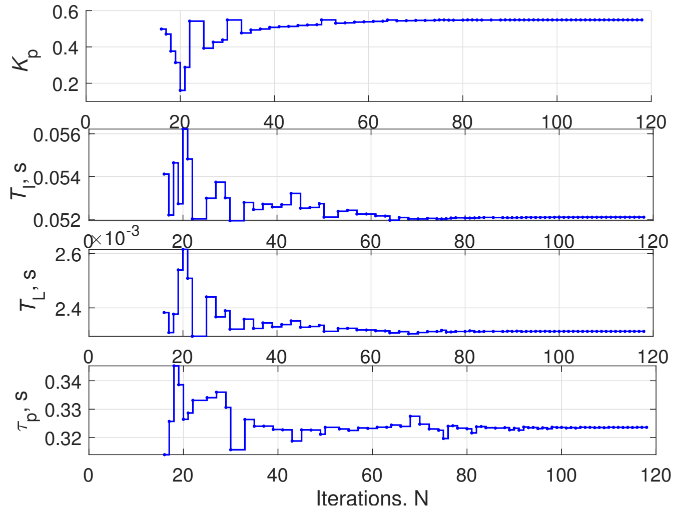

Fig. 3. Variation of the HO model parameters during optimization process

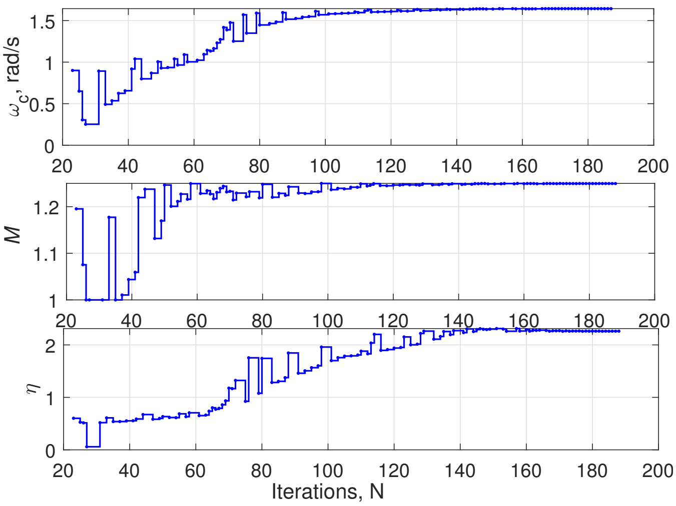

Fig. 4. Variation of the system parameters during optimization process

Figures 3, 5 show how the HO model parameters change depending on the iteration step N for linear and nonlinear models, respectively. Figure 4 demonstrates dependences of the system model parameters on the iteration step N for nonlinear system.

5. CONCLUSIONS

This paper proposes an algorithm for identifying the parameters of a human operator model for nonlinear control systems. The algorithm can be used to evaluate the controllability of a setup in terms of how much operator effort, control, or operation is required. It is also possible to identify parameters corresponding to unfavorable control practices that can lead to an accident. Modeling a human-machine system based on the proposed approach can reduce the time and resources allocated to semi-natural tests. It can be used in computer design to evaluate controllers or new controlled installations and various simulators. The proposed algorithm can also be applied to preliminary detection of the possibility of unacceptable behavior of a human operator in a closed loop of automated control systems, to prevent accidents, to train an inexperienced operator on the model of an experienced one, and also for using in driver warning systems by monitoring changes in the driver model parameters. In future studies, it is planned to obtain experimental results on the identification of a human operator model in full-scale experiments on various kinds of equipment.

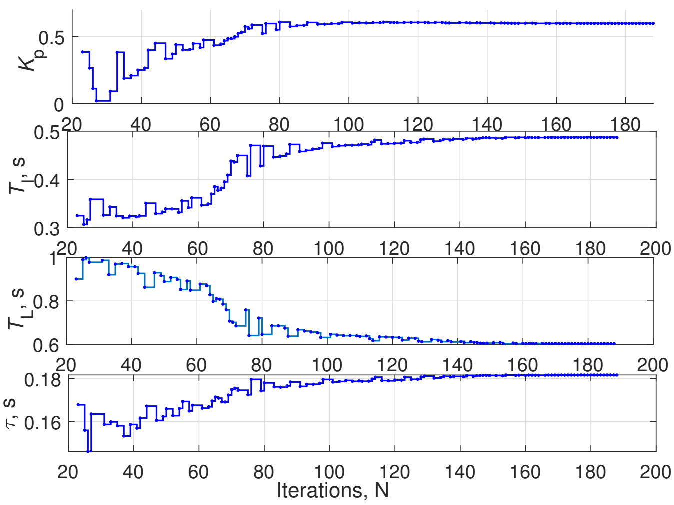

Fig. 5. Variation of the HO model parameters during optimization process

REFERENCES

Aizerman, M. and Freeman, E. (1963). *Theory of Automatic Control*. Pergamon, USA.

Andrievsky, B., Kudryashova, E., Kuznetsov, N., Kuznetsova, O., and Mokaev, T. (2018a). Hidden nonlinear oscillations in aircraft stabilization system with restrictions at the actuator control. *AIP Conference Proceedings*, 2046. doi:10.1063/1.5081524.

Andrievsky, B., Kudryashova, E., Kuznetsov, N., Kuznetsova, O., and Mokaev, T. (2019). Hidden oscillations in an active flutter suppression system and flight of a manned aircraft. *Mathematics in Engineering, Science and Aerospace*, 10(3), 357–371.

Andrievsky, B., Kuznetsov, N., Kuznetsova, O., Leonov, G., and Seledzhi, S. (2015). Nonlinear phase shift compensator for pilot-induced oscillations prevention. In *Proc. IEEE European Modelling Symposium*, 225–231. IEEE Press.

Andrievsky, B., Kuznetsov, N., and Kuznetsova, O. (2018b). Hidden nonlinear oscillations in controlled aircraft with saturated inputs. In *Proc. 15th International Conference on Control, Automation, Robotics and Vision (ICARCV 2018)*, 704–709. doi: 10.1109/ICARCV.2018.8581296.

Andrievsky, B., Kuznetsov, N., Kuznetsova, O., Leonov, G., and Mokaev, T. (2016). Localization of hidden oscillations in flight control systems. *SPIIRAS Proceedings*, 6(49), 5–31.

Brezenski, C. (1996). Extrapolation algorithms and pade approximations. *Applied Numerical Mathematics*, 20(3), 299–318.

Chetty, S. and Lakshmi, P. (1991). Computer aided evaluation of aircraft handling qualities. *IFAC Proceedings Volumes*, 24(4), 435–440. IFAC Symposium on Computer Aided Design in Control Systems, Swansea, UK, 15-17 July 1991.

Efremov, A., Tyaglik, M., Tyaglik, A., and Irgaleev, I.K. (2019). Developing the mathematical model of a pilot in a control manual preview tracking task. *Russ. Aeronaut.*, 62, 394–400.

Filatov, I. and Sharov, S. (1977). Investigation of parametric sensitivity of non-linear dynamic correcting devices. *Engineering Cybernetics*, 15(2), 166–169.

Font, R., García, J., and Ovalle, D. (2010). Modelling and simulating ballast tank blowing and venting operations in manned submarines. *IFAC Proceedings Volumes*, 43(20), 67–72. 8th IFAC Conference on Control Applications in Marine Systems.

Hess, R., Keith, M., and Hubbard, M. (2012). Modeling the manually controlled bicycle. *IEEE Trans. Systems, Man, and Cybernetics — Part A: Systems and Humans*, 42(3), 545–557.

Hess, R.A. (2016). Fast simulation in evaluating pilot/aircraft performance and handling qualities. *IFAC-PapersOnLine*, 49(32), 153–158. Cyber-Physical and Human-Systems CPHS 2016.

Hippe, P. (2006). *Windup in control. Its effects and their prevention.* Springer-Verlag London.

Jaiswal, S., Aman, R., Sopanen, J., and Mikkola, A. (2021). Real-time multibody model-based heads-up display unit of a tractor. *IEEE Access*, 9, 57645–57657.

Kleinman, D., Baron, S., and Levinson, W. (1970). An optimal control model of human response. part 1: Theory and validation. *Automatica*, 6, 357–369.

Klyde, D. and Mitchell, D. (2004). Investigating the role of rate limiting in pilot-induced oscillations. *Journal of Guidance, Control, and Dynamics*, 27(5), 804–813.

Kuznetsov, N.V. (2020). Theory of hidden oscillations and stability of control systems. *J. Comput. Syst. Sci. Int.*, 59, 647–668. doi:10.1134/S1064230720050093.

Leonov, G., Andrievskii, B., Kuznetsov, N., and Pogromskii, A.Y. (2012). Aircraft control with anti-windup compensation. *Diff. Equat.*, 48, 1700–1720. doi: 10.1134/S0012266112130022.

Mandal, T.K. and Gu, Y. (2016). Analysis of pilot-induced-oscillation and pilot vehicle system stability using UAS flight experiments. *Aerospace*, 3(4). doi:10.3390/aerospace3040042. URL `https://www.mdpi.com/2226-4310/3/4/42`.

McRuer, D. and Krendel, E. (1974). Mathematical models of human pilot behavior. Technical Report AG-188, AGARD.

McRuer, D.T. (1980). Human dynamics in man-machine systems. *Autom.*, 16, 237–253.

Mehra, R. and Prasanth, R. (1998). Bifurcation and limit cycle analysis of nonlinear pilot induced oscillations. In *Proc. 23rd Atmospheric Flight Mechanics Conf.*, 144–153.

Nelder, J. and Mead, R. (1965). A simplex method for function minimization. *Computer Journal*, 7(4), 308–313.

Phatak, A., Weinert, H., Segall, I., and Day, C. (1976). Identification of a modified optimal control model for the human operator. *Automatica*, 31–41.

Phatak, A. and Kessler, K. (1977). Modeling the human gunner in an anti-aircraft artillery tracking task. *Human Factors*, 19(5), 477–494.

Pool, D., Zaal, P., Damveld, H., van Paassen, M., and Mulder, M. (2009). Pilot equalization in manual control of aircraft dynamics. In *Proc. 2009 IEEE Intern. Conf. Systems, Man and Cybernetics*, 2480–2485.

Reid, L. and Drewell, N. (1972). A pilot model for tracking with preview. In *Proc. 8th Conference on Manual Control*, 191–204. Ann Arbor, USA.

Sharov, A. and Sharov, S. (1974). Investigation of parameters and frequency properties of certain nonlinear dynamic correcting devices. *Automation and Remote Control*, 35(8), 1219–1225.

Skorospeshkin, M., Sukhodoev, M., Timoshenko, E., and Lenskiy, F. (2015). Adaptive pseudolinear compensators of dynamic characteristics of automatic control systems. In *IOP Conf. Ser.: Mater. Sci. Eng.*, volume 124, 6.

Somov, S., Butyrin, S., and Somova, T. (2013). Modeling, optimization, simulation and animation of land-survey satellite motion. *IFAC Proceedings Volumes*, 46(19), 25–30. 19th IFAC Symposium on Automatic Control in Aerospace.

Tran, A., Sakamoto, N., Kikuchi, Y., and Mori, K. (2017). Pilot induced oscillation suppression controller design via nonlinear optimal output regulation method. *Aerospace Science and Technology*, 68, 278–286.

Tse, E. and Weinert, H. (1975). Structure determination and parameter identification for multivariable stochastic linear systems. *IEEE Transactions on Automatic Control*, 20(5), 603–613.

Zaitceva, I. (2019). Nonlinear oscillations prevention in unmanned aerial vehicle. In *Proc. XI Majorov Int. Conf. on Software Engineering and Computer Systems*, 8.