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The Dynamic Pilot Behavioral Models

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Abstract

This paper presents an analysis of dynamic human behavioral models focused on the action of pilots during flight. The linear dynamic models are used for the approximation of human behavior. Although, at present, the Tustin – McRuer model is the most widely applied tool, there are viable alternatives embodied in the precision model or the variants proposed by Tustin and Gross. All the models are considered and briefly described in this article. A substantial portion of the paper contains a simulation-based comparison of the discussed models, whose parameters are based on real measurements on a flight simulator.

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Keywords: pilot's behavior; Tustin-McRuer's model; dynamic models; flight simulator; human factor

1. Introduction

Currently, the human operator still constitutes and indivisible part of most control systems, which are thus denoted as Man-Machine Systems (MMS). A typical (but also critical) form of MMS is flight control, where even the slightest control action failure may result in a disaster. In such applications, special effort is made to analyze the properties of the control loop. [7] The following text comprises a description of frequently utilized human behavior models complemented with an example of appropriate verification; these aspects are further extended with a comparison of the models via simulations based on real measured data of a pilot's control actions.

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2. Dynamic pilot models

One of the eminent scientists in the field of modeling of pilots' behavior was Robert McRuer, whose argument is based on the assumption that pilots' behavior can be described via the theory of linear dynamic systems after accepting several simplifying hypotheses. During the 1960s, McRuer proposed the principle called Crossover law. According to this concept, a human being (a pilot) adjusts his/her control actions to comply with the controlled element. [1], [2] The Crossover principle later became the basis for further, more concrete models; their most widely used variants are described in the text below. [8]

2.1. The Precision model

Pursuant to the Crossover law, McRuer created a model including a description of the human neuromuscular system dynamics. This model is commonly denoted as the Precision model, and its simpler form is described by the relevant formula (1) [2].

$$F_H(p) = K_H \cdot \frac{T_L p + 1}{T_I p + 1} \cdot \frac{1}{\frac{p^2}{\omega_N^2} + \frac{2\zeta_N}{\omega_N} p + 1} \cdot \exp(-\tau p)\,, \tag{1}$$

where K_H is the pilot's gain, T_L denotes the time lead constant [s], T_I is the time lag constant [s], ω_N represents the natural frequency of the neuromuscular system, ζ_N denotes the damping for the neuromuscular system, τ indicates the pilot response delay [s], and p represents the Laplace operator.

The pilot modifies mainly the lag and the lead time constants, but the individual parts of (1) can be further simplified too. The typical values or ranges of some constants are presented in Tab. 1 [2], [6], [10].

Table 1. The typical values of certain constants for the Precision model.

Variable	Typical value
τ – the pilot response delay	(0.1 – 0.5) s
T_L – the time lead constant	(0.2 – 6.1) s
T_I – the time lag constant	(0.1 – 3.7) s
ω_N – the natural frequency of the neuromuscular system	about 20 rad.s^{-1}
ζ_N – the damping for the neuromuscular system	about 0.7

2.2. The Tustin-McRuer model

At present, the Tustin-McRuer model is the most widely used instrument for the modeling of pilots' behavior, see (2); its current form is based on the precision model [3], [5]. The oscillating component of the neuromuscular system is changed to the single neuromuscular constant T_N, whose value is usually about 0.1 s. This discussed variant provides less oscillating responses, and it usually constitutes a sufficiently accurate approximation of the pilots' response. We have

$$F_H(p) = K_H \cdot \frac{T_L p + 1}{(T_I p + 1)(T_N p + 1)} \cdot \exp(-\tau p)\,, \tag{2}$$

where K_H is the pilot's gain, T_L denotes the time lead constant [s], T_I represents the time lag constant [s], T_N expresses the time constant of the neuromuscular system, τ is the pilot response delay [s], and p denotes the Laplace operator.

2.3. The Gross model

The Gross model constitutes another simplification of the Precision or Tustin-McRuer models. The presented tool expects only the time lead constant T_L and the time lag constant T_I. The neuromuscular time constant is approximated by the single component of the pilot response delay τ_N. The form of the Gross model is shown in formula (3), which is expressed as follows [2], [4], [9], [10]:

$$F_H(p) = K_H \cdot \frac{T_L p + 1}{T_I p + 1} \cdot \exp[-(\tau + \tau_N) p] \tag{3}$$

2.4. The Tustin model

The scientist Arnold Tustin established his own model of human behavior already in 1944; he used the servomechanism theory for the analysis of manual control. The form of the transfer function describing human behavior is presented in (4) [1]. We have:

$$F_H(p) = K_H \cdot \frac{T_L p + 1}{p} \exp(-\tau p), \tag{4}$$

where K_H is the pilot's gain, T_L denotes the time lead constant [s], τ represents the pilot response delay [s], and p is the Laplace operator.

This model provides lower accuracy than the other instruments and is used only sporadically. In addition, it was later found out that human behavior cannot be described as a pure integrator. Therefore, this model is suitable especially for obtaining approximated results [2].

3. The measurement of the pilots' response

The basis of this experiment consists in the measurement of the pilot's control action as a response to a visual stimulus. In this case, the pilot's response to a step change of the aircraft altitude from the initial state H_0 [ft] is measured. The pilot's task is also to return the aircraft to the original altitude as quickly as possible and maintain the position; he or she could perform this by using only the aircraft elevator controls (the engine thrust is constant). The actual experiment is realized in collaboration with pilots trained at Brno University of Defense.

The description of the entire experiment is shown in Fig. 1, where $w(t)$ is the required aircraft altitude, $H(t)$ denotes the real aircraft altitude, and $e(t)$ represents the deviation between the required and the real aircraft altitude. We then have $e(t) = w(t) - H(t)$, i.e., the visual stimulus, and $dv(t)$ describes the elevator deflection, namely the pilot's response.

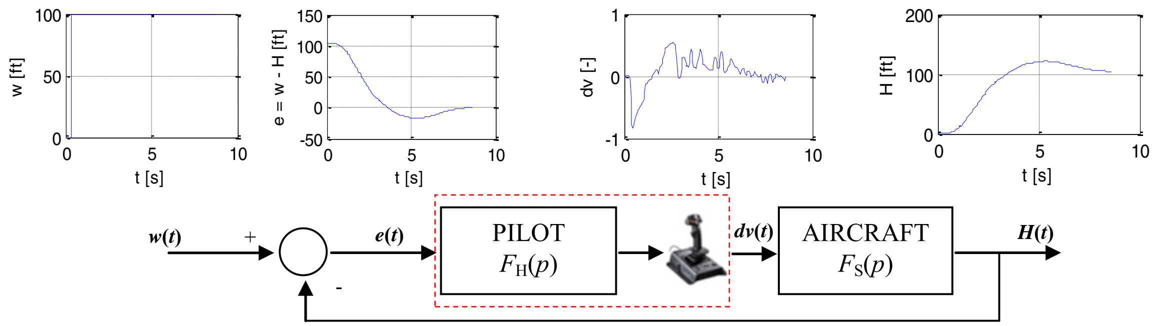

Fig. 1. A description of the experiment: the control loop with a human operator (a pilot).

We used the flight simulator operated by the University to monitor the control actions taken by the test subjects. This simulator is equipped with X-Plane 10, an advanced simulator program; the software facilitates the acquisition of various data and enables recording at the frequency of 20 Hz [5], [6]. The measurement and recording of the altitude H [ft], the elevator deflection dv [-], and the time t [s] are important assignments in this case. Further, a simulation with the twin-engine turboprop King Air C90B is used for this experiment.

In the diagrams, we can observe one instance of the measurement of pilot control action as a response to a visual stimulus (namely the information provided by the plane's altimeter). The visual stimulus is a step change of the required aircraft altitude, which equals 100 ft in the given case. The visual stimulus $e(t)$ and the pilot's response $dv(t)$ are shown in Fig. 2.

The MATLAB-based System Identification Toolbox is used as the instrument to model the parameters of the pilot's behavior identification. The applied models are those described in Eq. (1), (2), and (3).

After a large number of iterations, the System Identification Toolbox returns the required transfer functions. These functions, according to (1), (2), and (3), are approximations of a real pilot's control action taken as a response to a visual stimulus. In this context, we can express the following formulas:

- The Gross model (3):

$$F_H(p) = 0.17 \cdot \frac{4.41p-1}{0.82p+1} \cdot \exp(-0.4p);$$

- The Tustin-McRuer model (2):

$$F_H(p) = 0.15 \cdot \frac{5.59p-1}{(0.07p+1)(0.71p+1)} \cdot \exp(-0.3p);$$

- The precision model (1):

$$F_H(p) = 0.15 \cdot \frac{5.26p-1}{0.75p+1} \cdot \frac{1}{\frac{p^2}{25.8^2} + \frac{2 \cdot 0.8}{25.8} p + 1} \cdot \exp(-0.3p).$$

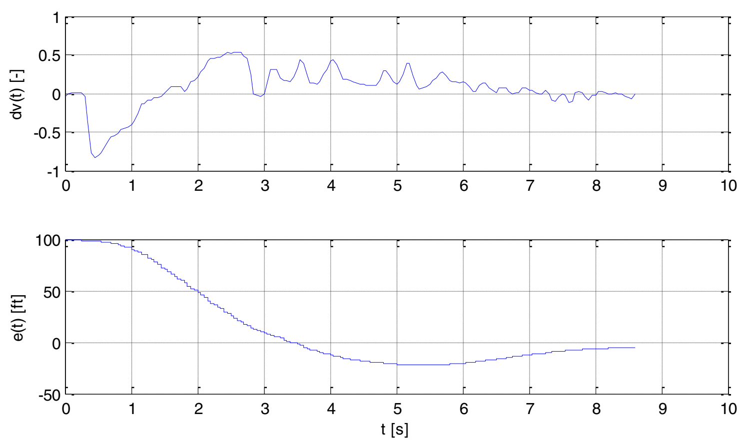

Fig. 2. The visual stimulus $e(t)$ and the pilot's response $dv(t)$.

The individual constants (Tab. 2) correspond to the theoretical assumptions according Tab. 1. The approximations are fairly accurate too (Fig. 3). Figure 3 presents an approximation of the original pilot's response carried out via the analyzed instruments, namely the Gross, the Tustin-McRuer, and the Precision models.

Table 1. The typical values of certain constants for the Precision model.

Variable	The Gross model	The Tustin-McRuer model	The precision model
K – the pilot's gain	0.17	0.15	0.15
τ – the pilot response delay	0.4 s	0.3 s	0.3 s
T_L – the time lead constant	4.41 s	5.59 s	5.26 s
T_I – the time lag constant	0.82 s	0.71 s	0.75 s
ω_N – the natural frequency of the neuromuscular system	-	-	25.8 rad.s^{-1}
ζ_N – the damping for the neuromuscular system	-	-	0.8

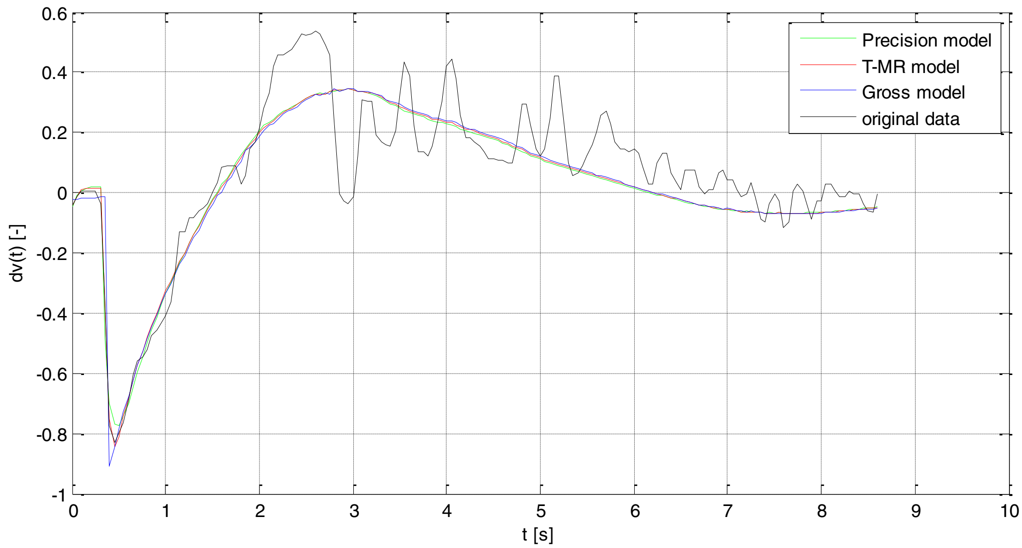

Fig. 3. An approximation of the original pilot's response carried out via the above-characterized models (Precision, Tustin-McRuer, Gross).

Conclusion

The aim of this paper was to describe pilot behavior models and their application in approximating a real pilot's control actions. In their analysis, the authors compared the precision model with other related models, namely the Gross model and the Tustin-McRuer model. All of the approximations using the discussed models are very similar and the individual instruments are similar too, see Tab. 2. The approximations of real data are comparatively accurate. The models parameters, i.e., the time constants, the pilot response delay, and the frequency and damping of the neuromuscular system, correspond to the theoretical assumptions demonstrated in Tab. 1. The results shown, that approximation by most widely used Tustin-McRuer model gives sufficiently accurate results and its use is suitable for modeling of pilot behavior.

The next research assumes the nonlinearity including to obtaining more accurate description of pilot behavior.

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