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NONLINEAR PILOT IN THE LOOP PERFORMANCE USING A MODIFIED CROSSOVER MODEL

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Abstract

The present paper describes a modelling structure of the pilot during compensatory tracking tasks, when his/her behavior shows nonlinear characteristics such as command saturation. Unlike linear behavior, which is well described in the literature with frequency domain, as well as algorithmic time domain methods, nonlinear behavior is still an active source of research. The proposed model structure stems from experimental verification of the relationship between saturated pilot commands and threshold values on error rate.

Introduction

The human pilot behavior during control tasks is a fundamental component of the overall aicraft control loop. In fact, any situation where manual control is involved requires or has required at some point modelling of human performance.

Over the years, there has been a large amount of research in the input-output representation of manual control, with significant contributions especially for modeling linear and pseudo-linear tracking tasks. A variety of techiques were used based on frequency domain methods, as well as algorithmic time domain methods [1], [2], [3], [4]. Applications of these models have been in aerospace systems analysis [5], vehicle dynamics, and marine systems dynamics and control [6], [7], among others.

In the present work, the interest is focused on nonlinear behavior, which is still an area of active research [8], [9], [10]. Typical occurrences of this type of behavior can be found during gross maneuvering and target acquisition, and more importantly, during that phenomenon commonly known as pilot-induced-oscillations (PIO). This latter case is a very critical, and potentially catastrophic dynamic coupling between aircraft dynamics and pilot commands, which could yield unstable and energy-increasing oscillations [10]. Recent examples such as YF-22 and JAS 39 accidents have renewed interest in the understanding of PIO, including the capability of modeling the pilot behavior when actuators saturate.

Unlike the approach described in [8], where bang-bang type behavior was cast into a variable structure methodology, the main point of the proposed model is the experimental verification of a relationship between a saturated pilot command, as shown in Figure 1, and a threshold value of the error rate.

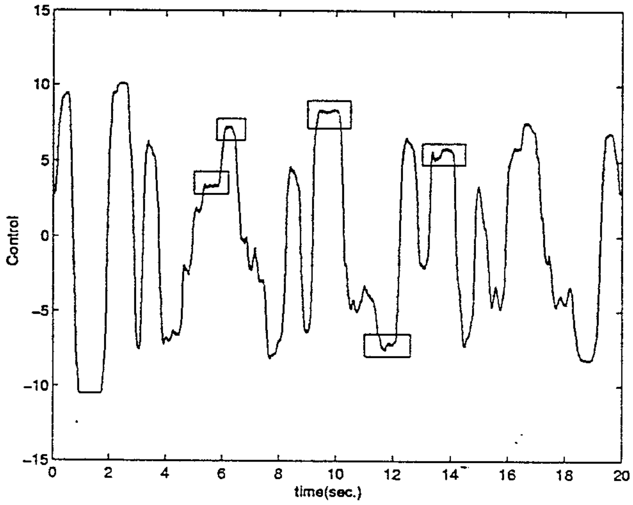

Figure 1. Saturation Levels in the Pilot Command

In order to implement the variable relay behavior, a sample-hold term was introduced, function of the error rate perceived by the pilot. The model was completed by an extended crossover structure [5] consistent with the experimental results during phases when the pilot command did not saturate. The model was validated against a simulation campaign, and stability of the closed loop system evaluated using Popov's method.

Model Development

A nonlinear behavior during a manual tracking task can be excited fairly easily using simple dynamics and forcing functions in a fixed base simulator facility as the

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one described in [8] and shown schematically in Figure 2. If we consider a second order plant dynamics given by

$$Y_c(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega s + \omega_0^2} \qquad (1)$$

with forcing function $r(t)$

$$r(t) = 1.2\sin(7\omega_{base}t) + 0.8\sin(11\omega_{base}t) + 1.4\sin(14\omega_{base}t)$$

A relationship between a pilot behavior shown in Figure 1, and damping and base frequency can be found as depicted in Figure 3.

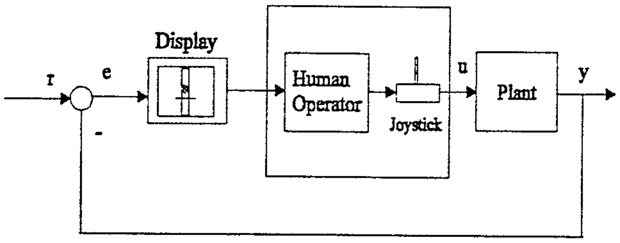

Figure 2. Schematic of Simulation Facility

Note that although significantly dependent on operator characteristics such as training, responsiveness, time delay, the behavior is general, indicating increasing nonlinear tendencies with decreasing damping and increasing bandwidth of the forcing function.

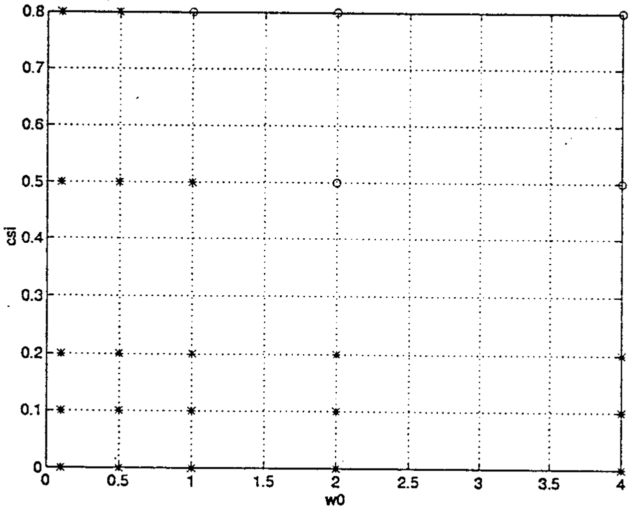

Figure 3. Typical Experimental Relationship between Plant/Input Parameters and Nonlinear Behavior

One of the main properties of the human operator during compensatory tracking, is the capability of extracting rate of change information of the displayed variable, with a varying degree of accuracy. This fact was known to be applicable to linear behavior [3], and the experiments carried out underlined it, especially in cases where the increased difficulty of the control task would lead to discontinuous activity by the operator. As an example of this capability, a linear relationship between control, error, and error rate of the form

$$u(t) = \alpha e(t) + \beta \dot{e}(t) \qquad (2)$$

was superimposed to an experimental time history as shown in Figure 4.

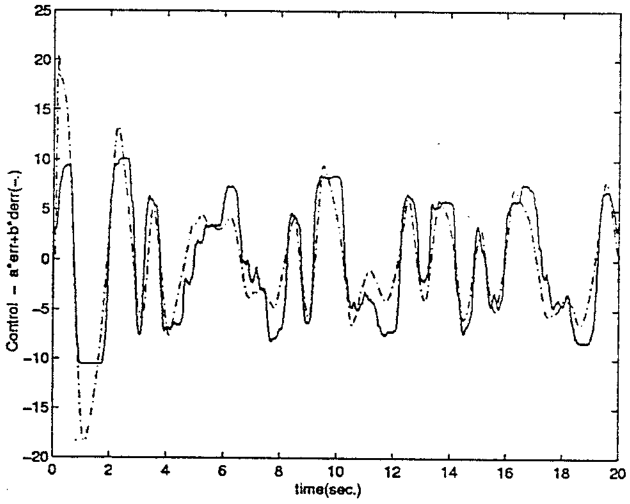

Figure 4. Relationship between Control and Error plus Error Rate

The weights in Eq. (2) are computed using a least squares procedure. The control signal in the figure is also translated according to the operator's time delay.

Figure 4 shows another interesting aspect of the human operator behavior, that is the presence of a hold in the control action, which could be interpreted as a saturated command (see the control valu of about −10 before the two seconds mark), as well as intentional, variable amplitude operator's saturated input. Based on open loop experimental data in fact, it appears that a hold comand corresponds to points where the error is at a maximum or minimum, while the error rate is below a threshold T_h.

$$\left|\frac{d(err)}{dt}\right| \le T_h$$

It is this occurrence that causes the discontinuity and nonlinearity of action by the human operator, and that will be modeled by a *Sample and Hold* component.

The block diagram in Figure 5 shows schematically the main components of the model. Error and error rate signals are derived from simulation. The Sample and Hold block is used to generate variable relay control action, following the processed displayed information taking the form of a "lead" controller. Operator's delay and input hard saturation are the other components.

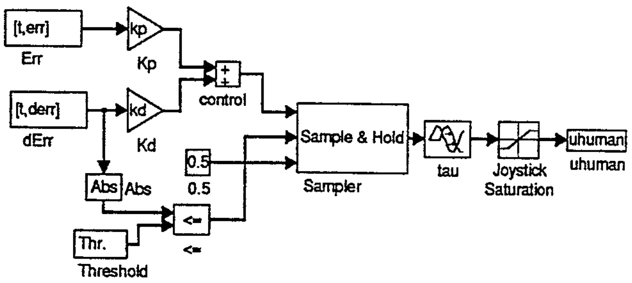

Figure 5. Components of the Model from Experiments

The structure just described, was then compared to experimental results, and an example is shown in Figure 6, with control output from the model, following error and error rate from experiment, matching the actual experimental control action by the operator. Of course, parameter tuning had been previously performed, with characteristics which will be presented in the next section.

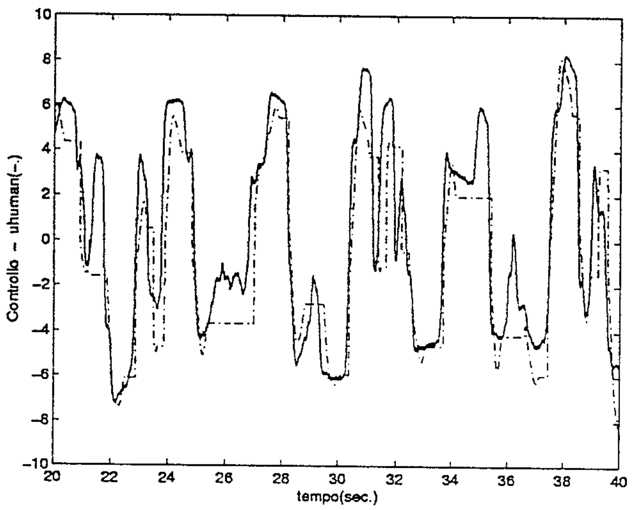

Figure 6. Open Loop Comparison with Experimental Data

Model Modifications

With reference to the pioneering work by McRuer [11], and additional experiments carried out during this work, the pure proportional-derivative action of the model was substituted with a more general equalization network of the form

$$Y_c(s)=K_p\,\frac{T_a s+1}{T_p s+1} \qquad (3)$$

The use of (3) allows higher flexibility in dealing with different plants, different control strategies, and a better adaptation to yielding integral action at crossover.

An important aspect of model validation was its closed loop behavior. In the analysis, moto noise and output noise characteristics were introduced, similar to the assumptions by Kleinmann [12]. The joystick used for input to the plant had variable sensitivity, adjustable by the operator during training tasks. This capability of course did not avid saturation in certain situations particularly difficult to control.

With the modifications described above, the model assumes a form that closely resembles the Crossover Model, except for its nonlinear component, and it is shown in Figure 7.

Due to these characteristics, it was named <u>HONLCOM</u> (Human Operator NonLinear CrossOver Model).

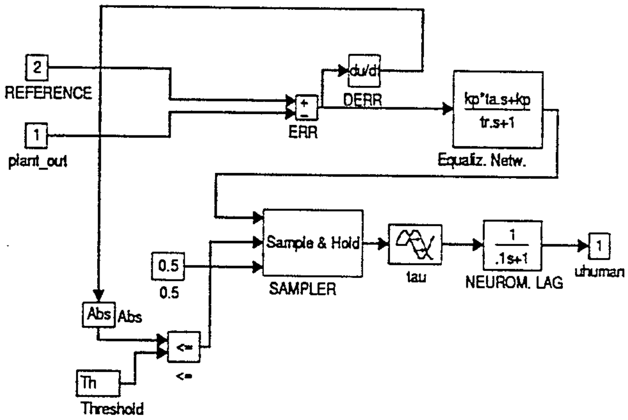

Figure 7. Block Diagram of HONLCOM Pilot Model

As shown in the figure, the overall time delay contribution was separated into a component due to visual , and central processing, and a neuromuscular component [12], partially adjustable with the task, although with A T_n roughly inversely proportional to the input bandwidth.

During closed loop control tasks, it is important to verify the stability of the system, which can not be asserted by standard crossover methods as in [11]. In general terms, the nonlinearity introduced in the HONLCOM could be represented by a variable amplitude satration, theefore conic sector techniques such as Popov's Criterion can be used for this purpose [13]. Popov's sufficient condition for global asymptotic stability of the origin requires that the linear system be asymptotically stable and controllable, the nonlinearity confined to a conic sector [0, k], and the existence of two positive numbers α, and ε such that

$$\forall\omega\geq 0;\ \mathrm{Re}\left[(1+j\alpha\omega)G(j\omega)\right]\geq -\frac{1}{k}+\varepsilon \qquad (4)$$

Tuning of the Parameters

One of the most critical aspects in the derivation of pilot models, and human operator's models has always been the tuning and identification of the parameters characterizing the model itself. As reported in [3], [5], [12], the optimal control model of the human pilot was a typical example of over-parametrization, which led to several simplifying assumptions over the years.

In our case, the tuning of the parameters was concentrated on the time delay, equalization network properties, and threshold value. This latter very critical, since mainly responsible for the nonlinear behavior.

Time Delay

The presence of time delay in the operator's performance, beyond neuromuscular lag is well known and documented. Several factors influence this parameter such as training levels, and task confidence among others. Classification of delay values was performed using a tracking task on a variable duty cycle square wave. Several subjects were tested, indicating ranges of delay according to the expertise acquired in performing the task.

Typically, ranges of 0.15-0.18 seconds, 0.19-0.23 seconds, and 0.23-0.3 seconds were found, corresponding to decreasing levels of training. It is worth noticing that such delay does not include the the neuromuscular lag assumed of the order of 0.1 seconds.

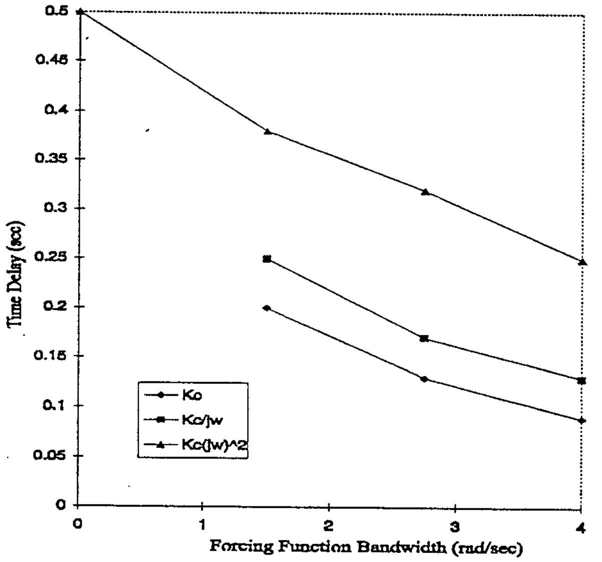

Figure 8. Experimental relationship between Time Delay and Forcing Function Bandwidth

The time delay is also adjusted taking into account the known dependency on the forcing function bandwidth, as described in [11], and shown in Figure 8.

Equalization Network

Tuning of the equalization network was performed along the lines of [11], however additional stability requirements had to be considered due to the non-linearity of operation. The procedure therefore consisted in a step that would ensure closed loop stability via Popov's method, and then additional parameter adjustment for the linear component, as in the crossover model of the human pilot.

If tuning of the equalization parameters T_r, T_a, and K_p were performed directly according to crossover model guidelines (which require a –20 dB/dec slope and some phase requirements), then unwanted oscillatory response would appear in some experiments due to unstable behavior from nonlinear control action. Using Popov's method, the problem is overcome although the relationship between crossover frequency ω_c and forcing function bandwidth needs to accommodate this variation, as shown in Figure 9.

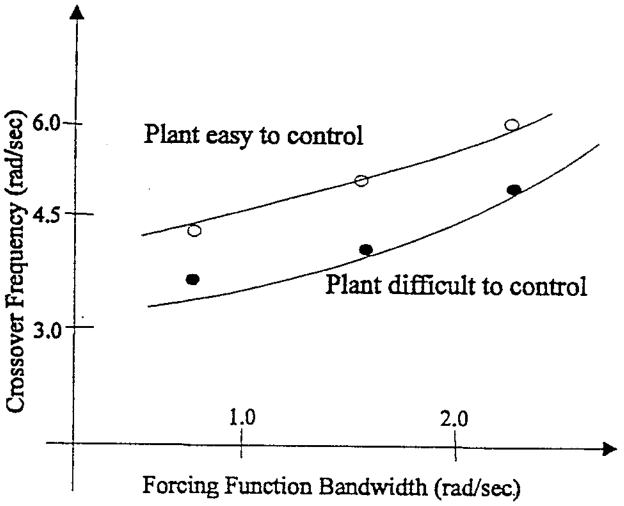

Figure 9. Experimental Relationship between Forcing Function and Crossover Frequency

Selection of Threshold Value

Tuning of threshold is directed toward the determination of its value in relation to the type of operator (expert, naïve, etc.), and the relative difficulty of the tracking task..

As described in the previous section, a relationship between error rate and saturation found to be a qualitative indicator of nonlinear behavior injection. Experimental results indicated however that matching threshold with error rate alone was not sufficient to identify a quantitative measure.

A much better result was obtained by matching threshold values with the error amount (%). Figure 10 indicates a definite, almost linear correlation between these two parameters.

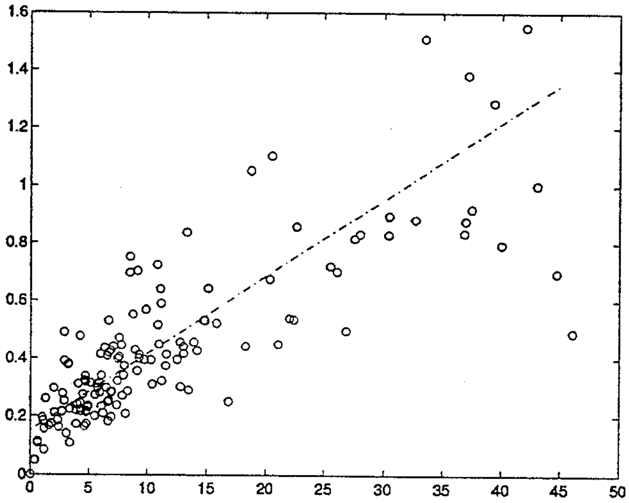

Figure 10. Correlation between Threshold and Tracking Error (%)

The results in Figure 10 indicate that the operator strategy is maintaining the stability of the plant when saturation is present even if the error increases.

Of course the correlation itself, while interesting from an analysis point of view, can not be used in the synthesis of the pilot model because the tracking error is not known prior to the task. The problem becomes therefore that of relating tracking error to parameters influencing the error itself. For compensatory tracking, the following parameters were selected:

- Difficulty of the task (plant to be controllerd)
- Forcing function bandwidth
- Training Level of the pilot

An extensive simulation campaign was carried out in order to determine correlation levels. The experiments were classified in classes of training levels and task difficulty. In all cases given the above values, the threshold would increase with the bandwidth of the forcing function. Figures 11 and 12 summarize our findings. In particular, Figure 11 indicates threshold values for given forcing function bandwidth and class of operators (expert, medium, naïve) as function of the task difficulty. Figure 12 shows instead gives threshold values as functions of task difficulty. Once this latter information is available, it can be related to the pilot training level.

Experimental Validation

Several closed loop experiments were carried out in order to validate the proposed model structure. Particular attention was devoted to the variation of crossover frequency with the forcing function bandwidth,

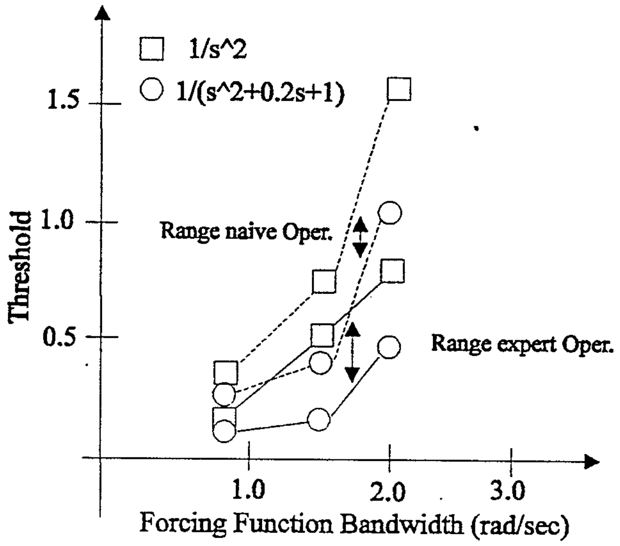

Figure 11. Summary Chart for Threshold Computation

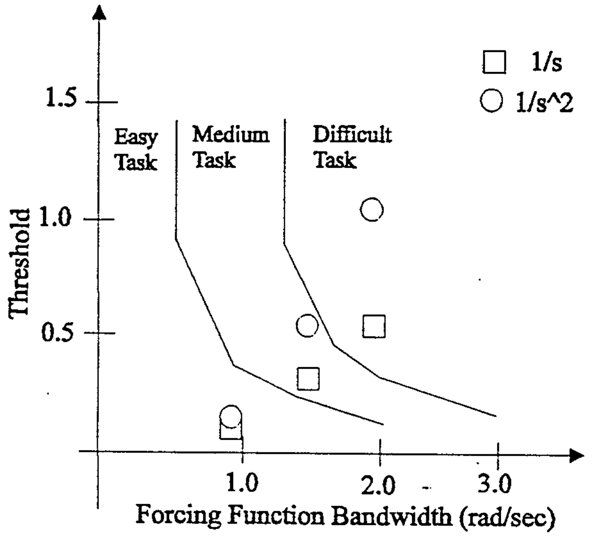

Figure 12. Threshold Computation

Adaptability of the model to represent different training levels (expertise of the operator), model properties with increasing task difficulty, and control of systems with zeros. Some of the results are illustrated in the following.

Adaptability

These next two examples show the capability of the model to represent operators with different levels of expertise. In both experiments the plant is represented by a second order system as in Eq. (1). The reference signal has a base frequency of 1.78 rad/sec. The first operator (trained) was modeled using Kp = 5.5, Ta = 1, delay of 0.12 sec, crossover frequency of 5.09 rad/sec from Figure

9, and threshold of 0.5 from Figure 12. Comparison between actual and modeled control action are shown in Figure 13, whereas the same comparison in terms of closed loop output are shown in Figure 14.

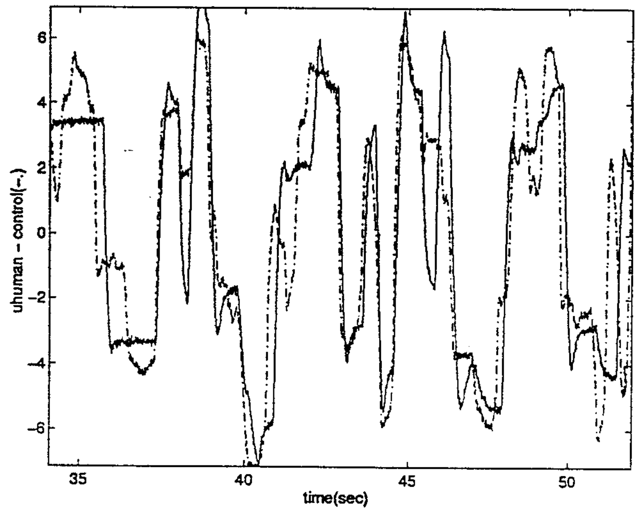

Figure 13. Experimental and Modeled Control Action

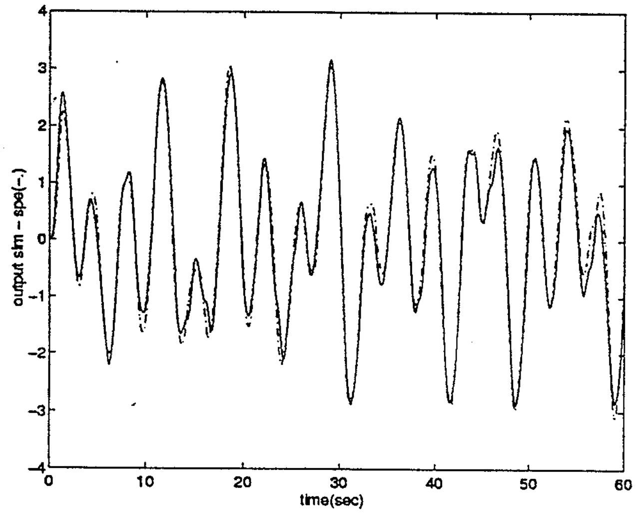

Figure 14. Experimental and Modeled Output

Similar results for a less trained operator are shown in figures 15 and 16 respectively. Values for the model were in this case: $K_p = 3.6$, $T_a = 1.6$, $T_p = 0$, crossover frequency 5.15 rad/sec, and threshold equal to 1.

Increasing Task Difficulty

In this class of experiments, the reference input is a sine wave, with constant base frequency of about 12 rad/sec, and an added zero mean noise with increasing variance. The objective was to test the model capability of replicating the time varying behavior of the operator. In addition, the model itself should be better suited to model nonlinear behavior present in the latter part of the experiment.

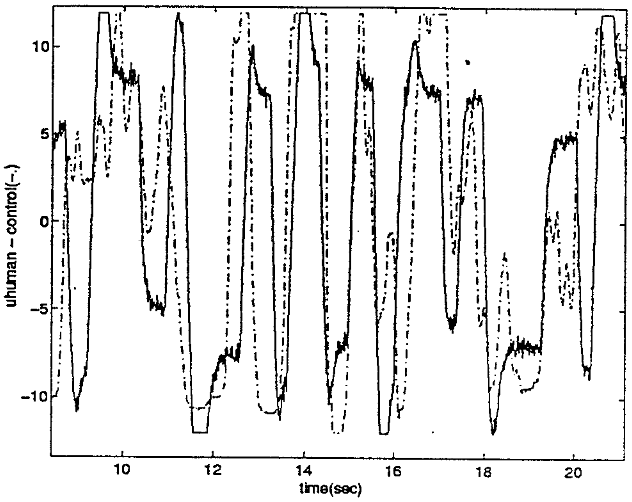

Figure 15. Experimental and Modeled Control Action

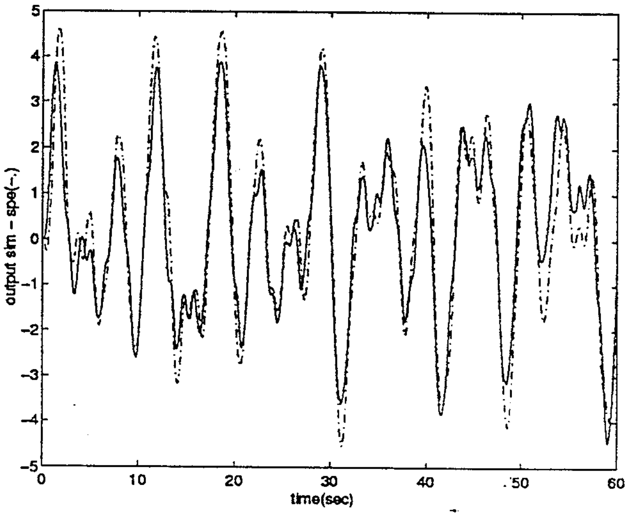

Figure 16. Experimental and Modeled Output

The modeling of the increasing difficulty is represented by a variable threshold given by

$$T_h = \begin{cases} 0.33 & t \in [0,20] \\ 0.60 & t \in [20,40] \\ 0.85 & t \in [40,60] \end{cases}$$

The comparison between experimental and model based control action over the entire experiment is shown in Figure 17 for each of the three sections. Another parameter used for comparison in all experiments has been the standard deviation of the control and output signals of the experimental data and model based data. This procedure, originally used in [12] gave satisfactory results, summarized in Table 1 for the current set of experiments.

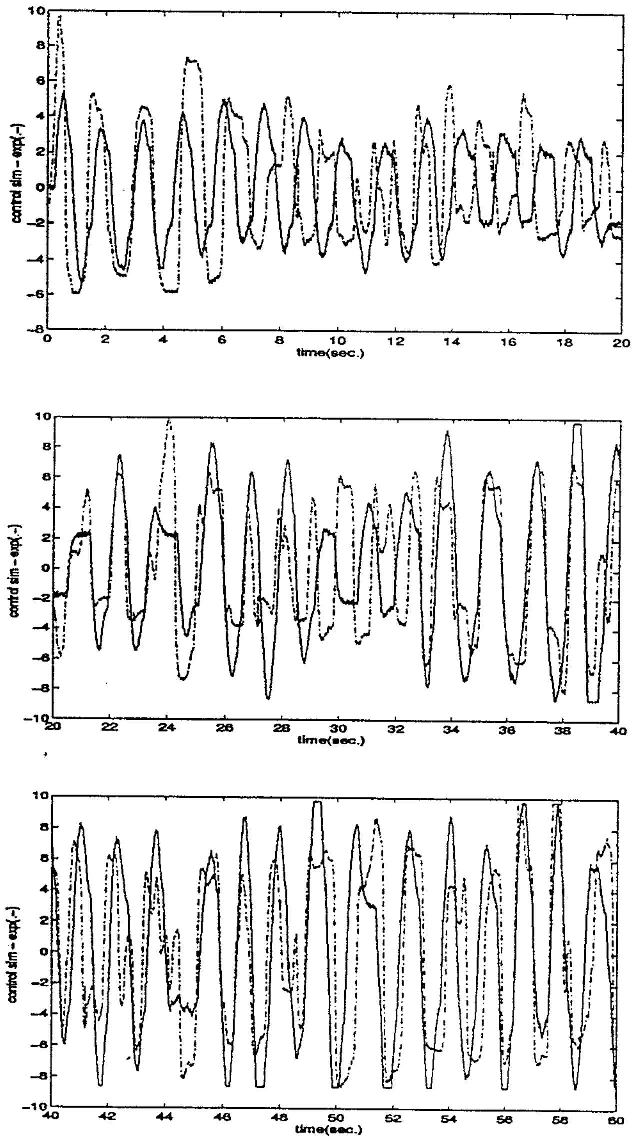

Figure 17. Experimental and Model Based Control Action, Increasing Difficulty Task

Table 1. Statistics for Experiment in Figure 17

Thres	*Standard Deviation Control*		*Standard Deviation Output*	
	Meas.	Theor.	Meas.	Theor.
0.5	3.5075	2.8332	1.2267	1.0800
0.7	4.3826	4.2004	1.1840	1.0669
0.8	5.3116	4.9636	1.1349	1.0816

Conclusions

The paper has presented the development of a model for pilot in the loop analysis, which extends the standard crossover model in order to include nonlinear behavior. The proposed model includes a threshold value, whose characteristics depend on reference signal bandwidth, task difficulty, and operator's training level. Tuning of the model parameters are affected by the above, although crossover frequency and equalization gains may be initially set according to the crossover model rule. The model was validated by extensive simulation of single axis compensatory tasks. Current work is directed toward the use of the model in pilot-induced-oscillations analysis, actuator saturation in the control loop, and evaluation of training levels of the operator.

Acknowledgments

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