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16. The Influence of a Prediction Display on the Quasi-Linear Describing Function and Remnant Measured With an Adaptive Analog-Pilot in a Closed Loop

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THE PREDICTION DISPLAY

The prediction display shows the desired value x_s, the actual value x_i and additionally the anticipated system output $x_v(t) = x_i(t+\tau)$. The predicted value x_v is computed through a Taylor series in which the number of derivatives used designates the order of prediction *(m)*. The prediction time is called τ. Refer to figure 1.

Investigating the manual attitude stabilization of one axis of a hovering VTOL aircraft, it was shown in several experiments, that a prediction display facilitates and improves the manual stabilization (refs. 1 and 2). The transfer function of the controlled system is $K_F/s^2(1+T_V s)$ with $T_V = \mathbf{0.4}$ sec and $K_F = 20$ cm/sec^2/full deflection. Refer to figure **1.**

The disturbance is taken from a pseudo-random noise generator, which consists of a 10 stage shift register with a **0.64** sec clock period, a digital to analog converter and a first order analog filter of the form $1/(1+j\omega)$.

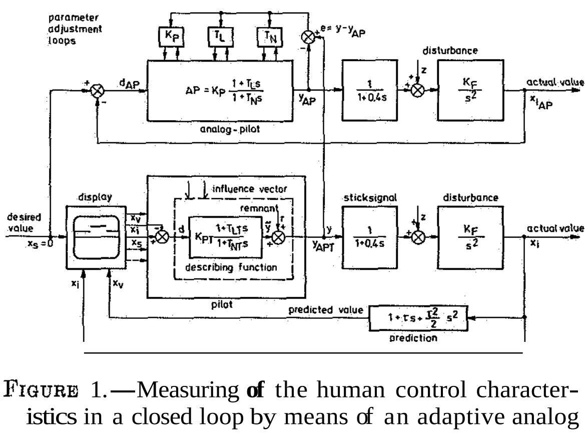

FIGURE 1.—Measuring of the human control characteristics in a closed loop by means of an adaptive analog pilot.

With a prediction display the damping of the man-machine control loop is increased and untrained test persons are able to stabilize the control loop from the first moment onward. The facilitation of a continuous control task by a prediction display can be shown by additional tasks. The improvement of the manual control is defined as a minimization of the rms value of the control deviation (control error e) with a simultaneous reduction of the rms value of the stick signal (stick deflection κ). The best prediction for the investigated system is a second order prediction

$$x_v = x_i + \tau\dot{x}_i + \frac{\tau^2}{2}\ddot{x}_i$$

with a prediction time of $\tau = 0.7$ sec. Refer to figure **2.**

The reason for the improvement of manual control by the additional pilot information about the anticipated system output must be seen in a change of the human transfer characteristics. This will now be explained by means of the parameter changes in a linear model.

THE HUMAN OPERATOR MODEL

The known application-orientated model of a linear describing function, a remnant, and an additional "influence vector" has been chosen to describe the human transfer characteristics, because much experience has been acquired for this model (ref. **3).** The describing function relating the stick signal y to the control deviation $d = 0 - x_i$ used is $AP(s) = K_P(1+T_L s)/(1+T_N s)$. The pre-

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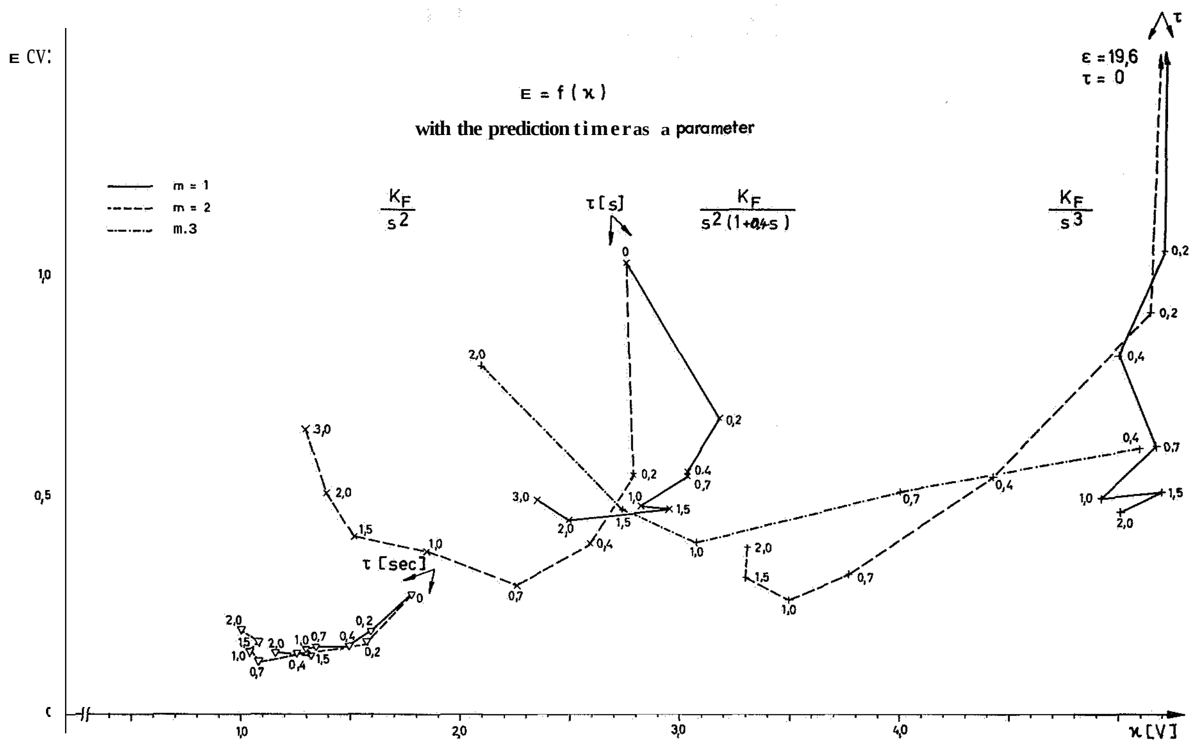

FIGURE 2.—Rms control deviation ϵ as a function of rms stick signal with τ as a parameter for the systems K_F/s^2, $K_F/s^2(1+0.4\text{ sec})$ and K_F/s^3.

dicted system output is always considered as additional information (like other a priori information) of the simulated task.

The remnant includes all nonlinear parts of the transfer characteristics as, for instance, observation and movement noise, the influence of an indifference threshold, stick positioning limits, and effects of discrete signal procession. The influence vector stands for all the parameters of the simulation and task which influence the transfer characteristics, which we attempted to hold constant during this investigation. The quasi-linear model is shown in figure 1.

To get an insight into the effect of different coefficient values on the mean square control deviation it is calculated without a remnant from the known disturbance.

Figure 3 is a 3-dimensional picture showing the mean square control deviation as a function of K_P, T_L, and T_N. The lowest control deviation can be obtained with high gain values. To obtain a stable loop in these cases T_L values must be high and T_N values low.

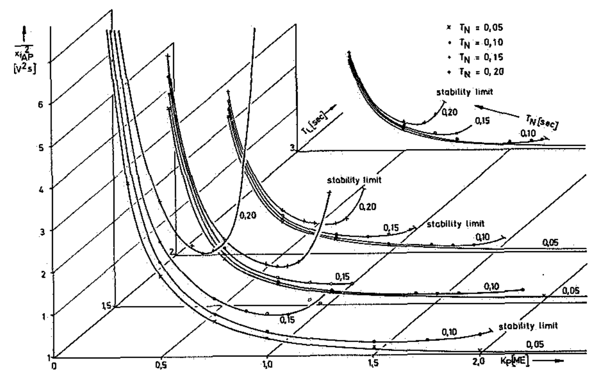

FIGURE 3.—The mean square value of the control deviation as a function of the analog pilot's coefficients.

THE CONTINUOUS ADAPTION OF THE MODEL

A model matching technique is used as a method of measurement because the simultaneous observation of the human and the model with its variable parameters yields a good view of the control process. When controlling a third order acceleration system, a great remnant portion is to be expected in the human output. The model matching technique is therefore used in a closed loop, that is, the adaptive analog-pilot works parallel to the manual control in its own loop. By this method of measurement the coefficients are not affected by the human remnant (ref. 4). Refer to figure 1. Under the assumptions that the structure of the model is chosen well and the adaption is finished the power density spectrum (PDS) of the remnant can be calculated directly from the PDS of the adaption difference e.

By means of the gradient method the coefficients K_P, T_L and T_N are adapted on-line, continuously and simultaneously, so that the difference of the output of the test person y and the analog pilot y_{AP} is minimized (ref. 5). The principle of adaption, for instance for the gain constant K_P is shown in figure 4. For adaption an even error function is defined:

$$f=\frac{1}{2}e^2=\frac{1}{2}(y-y_{AP})^2$$

and a modified gradient method is chosen for the continuous adaption of coefficients

$$\dot{c}_i=-k_i\frac{\partial f}{\partial c_i}=k_i\cdot e\cdot u_i$$

$\dot{c}_i$ describes the derivative of the desired coefficient, k_i represents the gain constant of the adaptive loops and

$$u_i=\frac{\partial y_{AP}}{\partial c_i}$$

describes the sensitivity functions. For each coefficient it is continuously computed. Since this is only valid for constant coefficients the adaption is performed iteratively. To begin with, initial values are chosen, then an adaption is performed and after that the measured coefficients are considered in the differential equations for the sensitivity functions before starting a new measurement.

The object of the experiments is a high speed of adjustment. The speed of adjustment is dependent on the number of parameters, the remnant, the power density spectrum of the disturbances, and the amplification factors of the adaptive loops. It is, after all, a stability problem. Since the stability of these measuring systems cannot be calculated so far, and since the entire method leaves a number of questions to be answered, it is tested by a test analog pilot with simulated remnant.

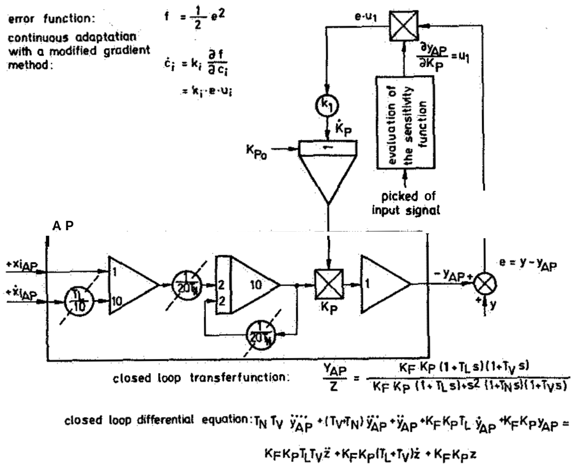

FIGURE 4.—The structure of the analog pilot and the K_P adaption loop.

THE TESTING OF THE MEASURING METHOD

The testing of the measuring method can be seen in figure 1. Instead of a human, a test analog pilot with a simulated remnant is operating in the control loop. Now, the known coefficients of the test analog pilot are measured by the analog pilot.

The investigation proved that the measuring method operates well. The remnant causes considerable reduction of the adjustment speed. After complete adaption the adaptive difference will not be zero, owing to the remnant. The difference is always minimized even if the known coefficients cannot be found exactly. The power density spectrum of the simulated remnant can be calculated from the adaptive difference. Therefore the power density spectrum of the remnant, occurring during experiments with the human can also be calculated.

THE MEASURING OF THE HUMAN CONTROL CHARACTERISTICS

For the investigation of human control characteristics a special experimentation technique was developed which provides a stationary attitude of the test persons. They were screened optically and acoustically. They were able to manage the control tasks owing to former experiments and were trained additionally for **1** week.

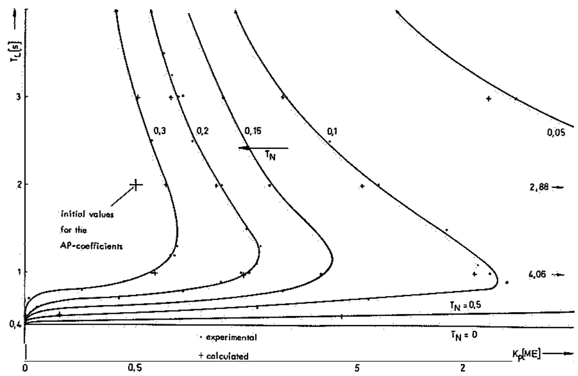

FIGURE 5.—The stability limit of the closed loop for 'different coefficients of the analog-pilot **(AP).**

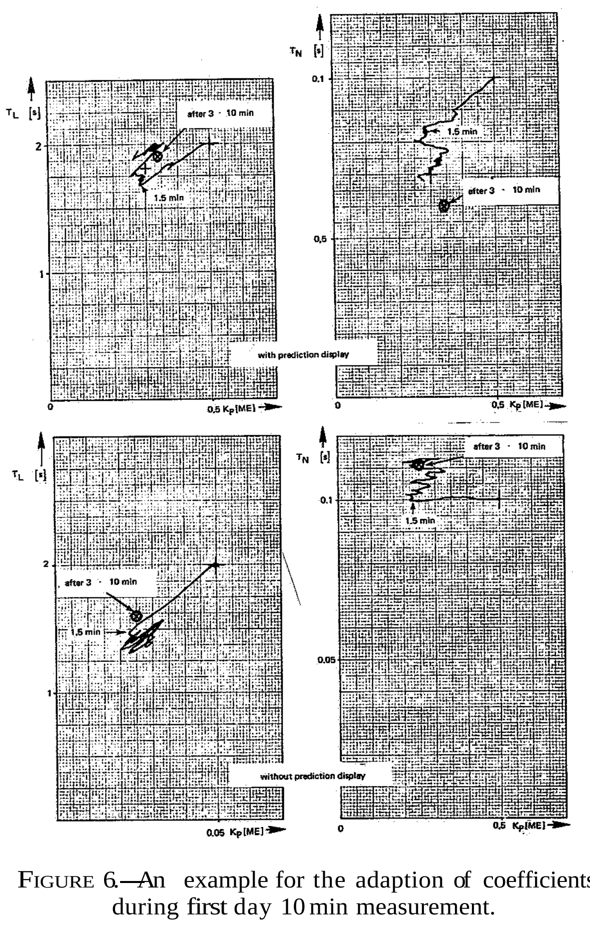

FIGURE 6.—An example for the adaption of coefficients during first day 10 min measurement.

The test lasted *10* minutes and was conducted twice during *3* days. The measuring time is a compromise between the frequency resolution and the statistic certainty of the results on the one hand and the exhaustion of the test persons on the other.

The initial values to begin with were derived from an investigation of the possible parameter space in respect to the stability of the control loop. Figure **5** shows the stability limits **as** a function of the parameters K_P, T_L, and T_N.

Figure **6** shows an example of the parameter adaption on the first day beginning with the initial values. The fast adaption within the first **1.5** min is obvious. The mean coefficient values, which were read after **3** days of tests were also recorded. They are shown in table *1.* **It** can be seen, that the test persons by means of the prediction display increase their effective gain constant and their effective lead constant and diminish their lag constant. This variation of coefficients already effects a reduction of the mean square value of the control deviation (see table *2* and figure *3).* The remnant decreases also by the prediction display.

TABLE *1.—Mean Values of Coefficients Measured by the Analog Pilot*

VP	Task	$\bar{K}_P[ME]$	$\bar{T}_L[s]$	$\bar{T}_N[s]$
K	With prediction	0.78	2.87	0.036
G	display	0.34	1.90	**0.060**
K	Without prediction	0.60	1.75	0.154
G	display	0.25	1.60	0.111

TABLE *2.—The Mean Square Values of the Control Deviation for the Test Persons and for the Adapted Analog Pilot*

VP	Task	$\bar{x}_i^2[V]^2$	$\bar{x}_{i\,AP}^2[V^2]$
K	With prediction	0.12	0.205
G	display	2.48	1.82
K	Without prediction	1.14	0.75
G	display	7.92	4.62

TABLE *3.—The Adaption Factor* $\tilde{\rho}$

Trial	VP	Task	$\bar{y}_{T_1}{}^2\bar{y}^2[V^2]$	$\bar{e}^2[V^2]$	$\tilde{\rho}^2$	$\tilde{\rho}$
E4	APT	Test	1.46	0.50	0.66	0.81
V9	K	With PD *	2.08	0.94	0.54	0.74
V10	K	Without PD	3.45	1.77	0.49	0.70
V11	G	With PD	1.08	0.36	0.67	0.82
v12	G	Without PD	1.06	0.49	0.54	0.73

* PD—prediction display.

For that part of the stick signal which can be explained by the analog pilot an adaption factor $\tilde{\rho}$ is defined

$$\tilde{\rho}^2 = 1 - \frac{\bar{e}^2}{\bar{y}^2}.$$

The adaption factor is a measure for that part of the human stick signal which is explained by the linear model and thus is a quality factor for the model. The results are depicted in table **3.** By means of the chosen simple model **70** to **80** percent of the human output can be explained.

Figure **7** shows an example of the power density spectra for the human stick signals, the analog pilot's stick signals, as well **as** the adaptive difference during control with and without prediction display. It is seen **(1)** that the prediction display increases the damping within the loop, and (2) the low frequency components of the human output are well explained by the analog pilot. The high frequency components remain in the adaptive difference.

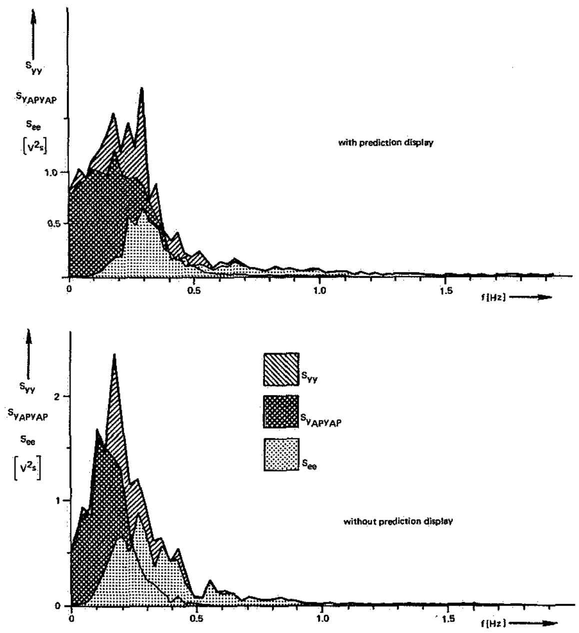

FIGURE 7.—An example for the power density spectra of the human stick signal S_{yy}, the analog pilot stick signal $S_{yap\ yap}$, and the adaption difference S_{ee}.

CONCLUSION

Summing up, one can say, that the effect of a prediction display on the human transfer characteristics can be explained with the aid of a quasi-linear model. The prediction display causes an increase of the gain factor K_P and the lead factor T_L, a diminishing of the lag factor T_N and a decrease of the remnant. Altogether, these factors yield a smaller mean square value of the control deviation and a simultaneous decrease of the mean square value of the stick signal.

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