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31. A Performance Measure for Manual Control Systems*

THEODOR A. DUKES AND PERSHING B. SUN

*Princeton **University***

A new performance measure is introduced for multivariable closed loop experiments with a human operator. The essential feature of the phase margin performance measure (PMPM) is that the performance of each control loop can be determined independently, with prescribed disturbance and error levels. A variable filter parameter is used as the PMPM within the loop and it assures a high workload at the same time. There is a straightforward relationship between the PMPM and the inner loop feedback augmentation that can be utilized in trade-off studies. An adjustment scheme that seeks the PMPM automatically is described as employed in a single loop control task. This task applies directly to the experimental study of displays for helicopters and VTOL aircraft.

INTRODUCTION

A closed loop dynamic system that includes the human operator in the loop poses many special problems to its designer. The man-machine interfaces and the processing of information inside man are both areas of particular concern in the efforts to represent the human controller with a quantitative model that can be used in system design. Any research in this area must be based on, or supported by, experimental evidence. Ultimately, the goal is always to provide means by which the values of alternative choices of system elements or characteristics (display, controller, system dynamics) can be compared. Besides the comparison of different versions of the same element, there is a considerable interest in trade-off studies, i.e., in establishing the relative merits when improvements are made in different elements; for example, in the controller's display vs. in the dynamics of the controlled system. In all cases a crucial choice must be made: a performance measure must be chosen as the basis for comparison in the experiments.

Performance measures can be separated into two broad classes: subjective and objective measures. Subjective measures are scales constructed to reflect a continuum of opinions, whereas objective measures are performance indices that can be measured by instruments or reduced from the test data. Subjective and objective measures do not necessarily yield the same results, although efforts have been made to match subjective measures with objective ones (ref. 1).

In quantitative manual control studies the independent and dependent variables must be chosen from the input, the output and the system parameters. Therefore, at least one of these is fixed in any experimental design in the sense that its characteristics are not varied. The independent variable is usually a syatem characteristic because most studies are aimed at finding the best choice of a parameter or structure. "Best" is usually defined in terms of a minimum or a maximum of a performance measure. On this basis three distinct types of manual control studies can be identified in terms of test variables, as indicated in the table shown on the next page.

There are advantages and disadvantages connected with any particular choice and some of these are discussed here briefly.

(1) The approach using fixed input characteristics is perhaps the most straightforward. It is

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Fixed	Varied (Independent var.)	Max. or min. (Dependent var.)
(1) Input	System	output
(2) output	System	Input
(3) Input & output	System	Auxiliary system

based on the assumption that the smaller the error output, usually in the rms sense, the better the performance. The required performance in an actual system is usually connected with the specification of an error tolerance rather than with minimizing the error. Even if such a tolerance is not given to the human operator, he develops a certain performance level that he considers satisfactory. This can be reflected in an insensitivity of the output performance in the case of a relatively low workload (ref. **2).**

(2) A high workload is provided and the system performance is related to a prescribed error tolerance in the second type of manual control studies (ref. **3).** The level of disturbance inputs is increased automatically if the error output is below the prescribed level and it is decreased if the output level is larger. The resulting input level is a function of the system characteristics and may not reflect realistic requirements for the tested system.

(3) The problem common to approaches **(1)** and **(2)** is that the range of the dependent test variable associated with the operation of the system may exceed the range of realistic magnitudes. The approach taken in reference **4** overcomes this problemby using fixed input and output characteristics. An auxiliary system is used to produce a variable extra workload. This workload is increased when the operator's performance with the tested system is better than specified and it is decreased when the performance is poorer. The auxiliary workload is measured in terms of the location of a variable unstable pole. A good correlation with opinion ratings has been achieved with this system despite the fact that the secondary task does not correspond to any realistic additional workload encountered in practice. Since the adjustment process is in the secondary task, this approach does not lend itself readily to trade-off studies in the primary system if the tested system involves more than one control loop.

A new approach is taken by the authors, aimed at trade-off studies of multivariable control systems with high workloads. The principle and the single loop mechanization of this approach are described in this paper.

THE PHASE MARGIN PERFORMANCE MEASURE (PMPM)

In connection with research on an integrated display for helicopters (ref. 5), it was found desirable to establish a method to determine how various aspects of the display could be evaluated in the multivariable control task of accurate flight path control. An experimental system suitable for this purpose was required to have the following characteristics:

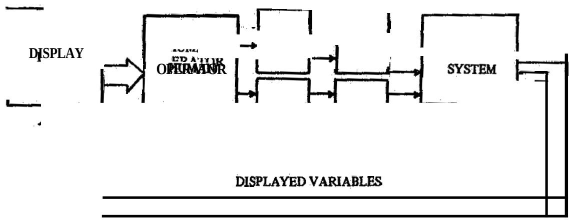
(1) A separate measure of performance for each control loop

(2) Disturbance and error levels to be controlled by the experimenter

(3) Assurance of high workload.

No existing test procedure could meet all three of these requirements. In order to provide individual performance measures for each control loop in the basic task, a system parameter in each loop must be chosen as dependent variable if input and output levels are to be fixed.

A controlled parameter in each loop can be used as dependent variable to increase the workload by making the system more difficult to control. This can be accomplished by inserting a variable filter in series with each controller of the system, as indicated in figure **1.** Variable system dynamics have been used before (ref. *6)* to determine the degree of instability an operator can control. In order to be close to realistic control tasks, the number of integrations between the controller and the controlled variable was chosen as the dependent variable system parameter. There is a very close relationship between this choice and feedback control augmentation, particularly in helicopters and VTOL aircraft. For example, a tight rate control loop can be considered as eliminating one integration; a tight attitude feedback loop closely corresponds to the elimination of two integrations.



$$G_{01}=\frac{\sqrt{1+K^2}}{S+K}$$

as K varies from infinity to zero. The phase shift of this filter varies gradually from 0" to 90" as shown in the figure. With G_{01} in series, the loop phase shift changes with varying K.

Assume that at the beginning of an experiment, with a prescribed disturbance level and $K=\infty$, the operator is able to control a variable

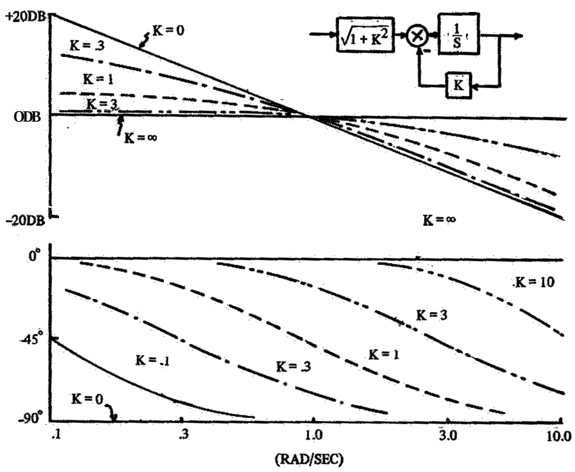


FIGURE 2.—Bode diagrams of variable filter.

matches the specified error. If K reaches an equilibrium at this state, it represents an additional phase lag or phase margin that can be handled by the operator with prescribed disturbance and error levels. K as a performance mea-

DESCRIPTION OF THE ADAPTIVE SYSTEM

The entire manual control system under consideration is shown in figure **3.** This system includes the adaptively controlled element, a model of the pilot equalization, the display feedback, and the input disturbance to the controlled element.

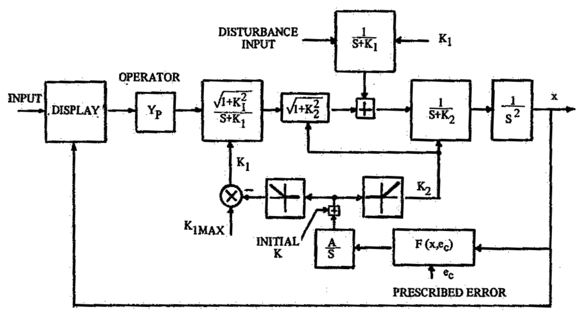


FIGURE 3.—Block diagram of the control loop and the adjustment loop.

Adaptive Filter Adjustment

The adaptively controlled element consists of two variable first order filters which are in series with two fixed integrators. The variation of the filter parameters K_1 and K_2 is produced by the integrated output of the performance calculation network, denoted by $F(x,e_c)$ where e_c is the prescribed error level. The performance calculation is obtained by comparing an even function of the error output with e_c. Continuous variation over a range of two integrations, corresponding to approximately 0° to 180° phase shift, is provided by the filters. As the adjustment loop integrator output varies from a positive maximum value to zero, K_2 varies from $K_{2\max}$ to zero while K_1 remains at $K_{1\max}$. As the integrator output decreases further from zero to a negative maximum range, K_2 remains zero and K_1 varies from $K_{1\max}$ to zero. The maximum values of K_1 and K_2 are chosen so that the phase shift produced by the filter approximates zero within the bandwidth of interest.

If the operator's performance is poorer than the prescribed level, K increases; if the system error is less than the prescribed level, K will decrease. In the case of a VTOL aircraft at hover, e.g., the equilibrium value of K may be viewed as an indicator of the amount of stability augmentation necessary to achieve a prescribed accuracy with a given disturbance level.

Disturbance Input

The disturbance input is entered into the system of figure 3 so as to resemble accelerations resulting from the aerodynamic moments produced by gust inputs. The disturbance is passed through the variable filters with unity filter gains, corresponding to the decreased effect of the disturbance as inner loop feedback gains are increased.

The input gust spectrum employed in handling quality studies of VTOL aircraft at hover is often produced by passing the output of a random noise generator through a first order filter with a break frequency of 0.314 rad/sec (refs. 7 and 2). In order to facilitate a relatively simple measurement of the human pilot transfer function, a random appearing function consisting of discrete frequencies is preferred (ref. 8). Consequently, the desirable input noise spectrum is made up of discrete frequencies with an amplitude envelope approximating a first order filter.

Control Loop Dynamics

For the analysis of the control loop dynamics, a simple linear pilot model is assumed. If the position error is the only element presented on the display, the pilot must generate a low frequency lead equilization, $Y_p = K_p(T_{Lx}s+1)$, in order to achieve stability for the closed loop system (ref. 8). It is assumed that the time delay portion of the pilot transfer function has a negligible effect on the positioning loop dynamics (ref. 2). The root locus plot in figure 4 indicates the variation of the closed loop roots as functions of the pilot equalization and the filter pole locations. For a given pilot equalization, with fixed T_{Lx} and K_p, the closed loop system damping decreases as K_2 decreases. When K_2 becomes less than $1/T_{Lx}$ the closed loop system becomes unstable. In the illustrated case K_1 remains $K_{1\max}$ since K_2 is determined by the characteristics of the disturbance input, the prescribed output error level and the pilot transfer function.

If both position and velocity errors are presented on the display, the pilot model can be represented by $Y_p = K_p(T_{Lx}s^2 + T_{Lx}s + 1)$. In this case, K_2 can be zero and K_1 becomes the variable parameter. This is shown by the root locus plot in figure 5; again the system damping decreases as K_1 decreases.

The display parameters such as display variables and display gains have been incorporated into the pilot equalization in order to show the

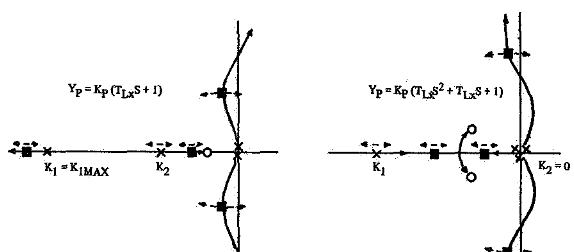


FIGURE 4.—Effects of the operator's gain and lead time constants.

general trend of the closed loop system dynamics. In practice, with a human pilot in the loop, the pilot's equalization parameters can be measured experimentally and the display gains are calculated from the particular display used in the experiment.

PERFORMANCE MEASURE AND THE PARAMETER ADJUSTMENT LOOP

Equilibrium Value of the Performance Measure K

Assuming a random input and a given form of the display-pilot feedback equalization, the mean square error can be calculated from the Phillips integral (ref. 9) as a function of the input and the final system parameters. Since in equilibrium the output of the system is at a prescribed level, the equilibrium value of K can be expressed as a function of the feedback and input characteristics and the prescribed output level.

Assuming again that only the position error is displayed and that the pilot transfer function is

$$Y_p = K_p(T_{Lx}s+1) \qquad (2)$$

the closed closed loop error can be expressed as

$$E(s) = \frac{N(s)}{s^3+Ks^2+K_pT_{Lx}(1+K^2)^{1/2}s+K_p(1+K^2)^{1/2}} \qquad (3)$$

where $K=K_2$, since $K_1=K_{1\,max}$, and the effect of the first filter on the closed loop dynamics is negligible.

$$N(s) = \frac{\sqrt{4\alpha \overline{n^2}}}{(\alpha s+1)} \qquad (4)$$

describes a filtered noise input with a cut-off frequency at $1/\alpha$ and a mean square value of $\overline{n^2}$.

From the Phillips integral table, the resulting mean square error is obtained

$$\overline{e^2} = \frac{2\alpha \overline{n^2}}{K_p^2(1+K^2)(KT_{Lx}-1)} \left[\frac{\alpha^2 K_p(1+K^2)^{1/2}(KT_{Lx}-1)+K(\alpha K+1)}{\alpha^2 K_p(1+K^2)^{1/2}(T_{Lx}+\alpha)+(\alpha K+1)}\right]. \qquad (5)$$

The ratio of the rms error to the rms noise level is plotted in figure 5 as a function of the equilibrium K. The increase in rms error as K decreases can be attributed primarily to the decrease in system damping.

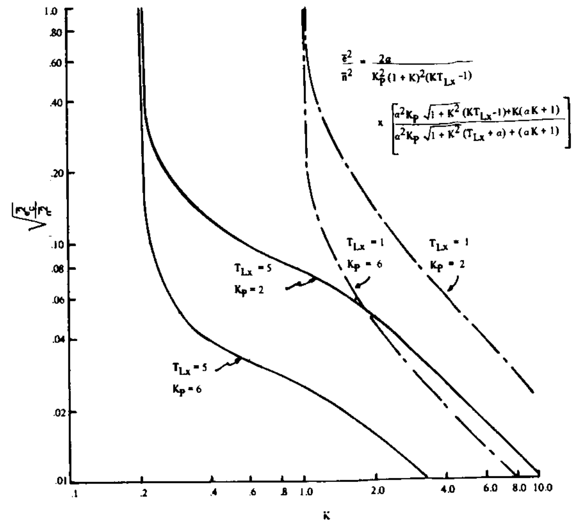


FIGURE 5.—Equilibrium values of the performance measure K.

The Parameter Adjustment Loop

In establishing the described adaptive system as a useful research tool, the importance of the choice of the parameter adjustment scheme cannot be over-emphasized. Crucial criteria in the selection of the adjustment scheme include the following:

(1) The scheme should adjust the performance measure automatically

(2) It should have no influence on the equilibrium value of the adjusted parameter

(3) The parameter should converge to its equilibrium value within the duration of the test run

(4) There should be little variation of the parameter about the equilibrium

(5) The mechanization of the scheme should be simple.

In the past, much effort has been spent on the study of various parameter adjustment schemes in different types of adaptive systems (refs. 10 and 11). The results of these studies depend heavily on the specific nature of the adaptive systems investigated. Furthermore, since the nature of the operator-display portion of the manual control system is generally not specified, it is difficult to draw analogies between the system discussed in this paper and other existing adaptive systems.

The following adjustment schemes were considered:

Scheme a.—

$$\dot{K} = A(x^2 - e_c^2) \tag{6a}$$

Scheme b.—

$$K = A \log (x^2/e_c^2) \tag{6b}$$

Scheme c.—

$$K = A \text{ sgn } (|x| - e_c) \tag{6c}$$

where

$\dot{K}$ = parameter adjustment rate
A = adjustment loop gain
e, = prescribed error level
x = system error output.

A graphical representation of these functions is shown in figure 6.

Scheme a is the simplest to mechanize. The parameter adjustment rate is proportional to the differencebetween the mean square values of the system error and the prescribed error. The principal difficulty with this scheme can be observed readily in figure 6. The adjustment rate is highly unsymmetrical about the equilibrium point $x^2 = e_c^2$. In the region of $x^2 < e_c^2$, the maximum K, at $x = 0$, is e_c^2, usually a small value. In the region of $x^2 > e_c^2$, K increases rapidly with *x* and becomes very large at high values of x^2/e_c^2.

The result is demonstrated in Figure 7(a). The unsymmetrical nature of the adjustment and the large variation in K is evident.

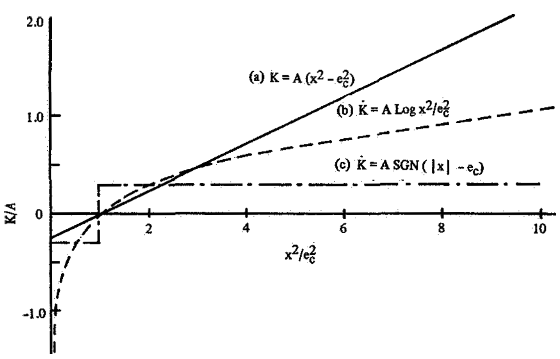


FIGURE 6.—Adjustment laws for the performance measure.

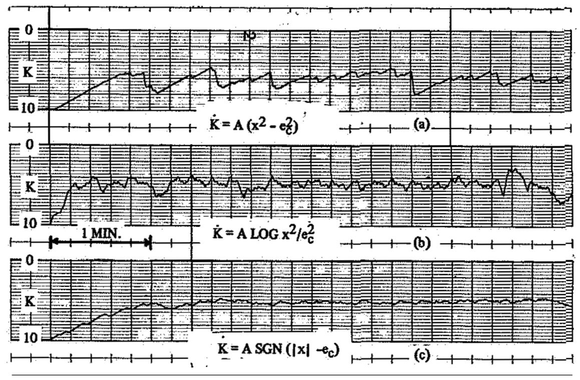


FIGURE 7.—Adjustment loop dynamics with random disturbances and $Y_p = K_p(T_{Lx}s + 1)$.

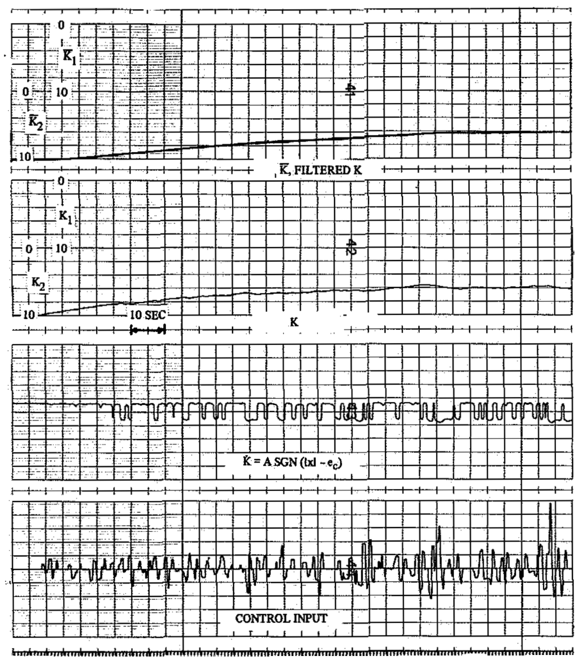


FIGURE 8.—Typical traces of the adjustment loop dynamics with a human operator.

Experimental results indicate that the adjustment loop dynamics become less oscillatory in nature when the loop gain is reduced. This benefit, however, is coupled with an undesirable increase in the time required to reach the equilibrium K value.

Scheme b does not exhibit the difficulties presented by scheme a. The adjustment rates are reduced at high x^2/e_c^2 and increased at low x^2/e_c^2, providing a more symmetrical parameter adjustment about the equilibrium point of $x^2 = e_c^2$. The negative infinite $\dot{K}$ at $x = 0$ indicated in figure 6 is naturally limited by the mechanization. This scheme works quite well in practice; however, the adjustment rates at the two ends of the x^2/e_c^2 scale still appear too high. As a result, the variation of K around its equilibrium value, for lightly damped control systems, is still larger than desired, as illustrated in Figure 7(b).

Scheme c is a bang-bang adjustment rule which is symmetrical about the equilibrium point at $x^2 = e_c^2$. It is simple to mechanize, and the result obtained with this scheme is comparable to that of scheme b.

With a reduced setting of the bang-bang level at approximately one-third, which is equivalent to reducing the loop gain by a factor of 3, a typical result is shown in Figure 7(c). A relatively smooth convergence in K to its equilibrium value with small variations is obtained.

A sample of experimental runs with the bang-bang adjustment scheme c and a human operator in the loop is shown in figure 8.

CONCLUSIONS

The phase margin performance measure established inside control loops is applicable to multivariable control systems when both the disturbance level and the error tolerance are specified. It features the following properties:

(1) A performance measure can be obtained for each control loop.

(2) A high workload condition is created automatically.

(3) The performance measure can be related directly to inner loop closure requirements.

(4) Trade-off studies between inner loop feedback augmentation and other parameters of system elements (displays, controllers, etc.) can be easily implemented.

A relatively simple mechanization with bang-bang control in the automatic adjustment of the performance measure results in quite satisfactory adjustment dynamics.

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