Development of Pilot-in-the-Loop Analysis

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PILOTED aircraft, to be effectively used, have always required a satisfactory match of the aircraft characteristics (including vehicle dynamics, control manipulator, stability augmentors, displays, etc.) with the controller properties of the human pilot. An agreeable marriage is not intrinsically achieved in the design process, so the provision of proper aircraft flying qualities has often posed serious problems which the designer must solve. Until fairly recently these solutions relied very heavily on intuitive cut-and-try procedures. Over the years this approach fostered many of the adventures and uncertainties of flight testing.

The desire to handle aircraft stability and control problems in a more analytical fashion was recognized long ago. For example, before World War II Koppen stated[1]:

> "Since the controlled motion of an airplane is a combination of airplane and pilot characteristics, it is necessary to know something about both airplane and pilot characteristics before a satisfactory job of airplane design can be done."

But the central difficulty in accomplishing a pilot/vehicle analysis was recognized earlier still. For example, W. Crowley and Sylvia Skan remarked in a 1930 Aeronautical Research Committee report[2]:

> "A mathematical investigation of the controlled motion is rendered almost impossible on account of the adaptability of the pilot. Thus if it is found that the pilot operates the controls of a certain machine according to certain laws, and so obtains the best performance, it cannot be assumed that the same pilot would apply the same laws to another machine. He would subconsciously, if not intentionally, change his methods to suite the new conditions, and the various laws possible to a pilot are too numerous for a general analysis."

Actually, matters are even worse than Crowley and Skan recognized; for while much of the pilot's dynamic behavior is governed by the aircraft dynamics, many additional factors also affect his properties.

Key Variables which Affect the Pilot

The pilots' dynamic characteristics when operating as a controller are affected by several physical, psychological, physiological, and experimental variables. They will be subsumed here under four categories, Fig. 1.

Task Variables

Task variables comprise all the system inputs and those control system elements external to the pilot which enter directly and explicitly into the pilot's control task. Stability of the closed-loop system is always a necessary, though not sufficient, control requirement. Consequently, the pilot's dynamics are profoundly affected by the display and controlled element dynamics, because his properties must be adapted to provide the necessary loop stability. The characteristics of the other task variables, i.e., disturbance inputs and command inputs related to the mission and control strategy, also exert direct influences on the pilot's dynamics, although their effects are more in the nature of adjustment and emphasis than of change in fundamental dynamic form.

Environmental Variables

The state of the environment external to the pilot is shown as the vector ϵ. Included as components of this vector are such factors as ambient illumination, vibration, temperature, and acceleration (to the extent that this is superimposed on, rather than controlled by, the pilot).

Procedural Variables

The procedural variables, denoted by the vector π, include such aspects of experimental procedure as instructions and order of presentation, as well as some of the less obvious effects on so-called behavior as can be inappropriately "revealed" when improper statistical analysis procedures are used (e.g., procedures which depend for their validity on questionable assumptions). In the latter case what constitutes the pilot's "behavior" can be affected materially simply by improper choices in the experimental design and statistical data analysis. Meticulous attention must be paid to the procedural variables because they are *so* important to the accuracy and generality of the experimentally-based conclusions.

Pilot-Centered Variables

The operator-centered variables, denoted by the vector σ, include the characteristics the pilot brings to the con-

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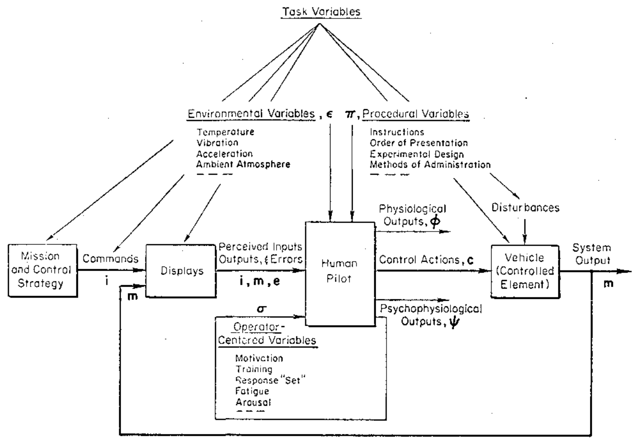

Fig. 1 Variables affecting the pilot-vehicle system.

trol task: training, motivation, "set" to respond, physical condition, etc. Many of these factors are difficult to quantify in terms meaningful to a given experiment. They can, however, at least be graded qualitatively by pretest, interview, etc., or controlled or modified by procedures (therefore there may be some interaction between π and σ).

Human Pilot Behavior and Description

To complicate matters further, consider what is meant by human behavior. The most obvious aspect of human dynamic behavior in a control task is the human pilot's *control activity* within that task. In many respects this is the paramount human property, for more often than not it is to attain that activity that the human is there. However, associated with the control actions are physiological and psychophysiological outputs, the vectors φ and ψ. These include status indicators of the human's internal environmental control systems, such as respiratory rate and volume, heart rate and blood pressure, rate of sweating and body temperature, etc., as well as such highly structured but nonetheless subjective indications of workload and pilot behavior as Cooper-Harper pilot ratings.

In the context to this point, the human pilot is a multi-input, multi-output device of enormous complexity. The inputs are signals arising from the task variables and the environmental stressors while the outputs include physiological and psychophysiological activities as well as control actions. An appropriate descriptor of a human in this context is one which relates control, physiological, and psychophysiological outputs to control and environmentally-derived inputs.

When the key variables are approximately time stationary over an interval of interest, the pilot-vehicle system can be modeled as a quasilinear system in which the relationships between pertinent measures of system input and output signals have some linear correlation in spite of the possible existence of nonlinearities and short-term (relative to the observation interval), time variations. When attention is focused on control actions, as shall be done henceforth, the pilot's control activity is capable of being modeled as a stationary process for a very large number of circumstances.

In a quasi-linear system the response for a given input is divided into two parts—describing function components which correspond to the responses of equivalent linear elements driven by that input, and a "remnant" component which represents the difference between the response of the actual system and an equivalent system based on the linear elements. Quasi-linear models consisting of describing function plus remnant descriptions for random-appearing inputs and disturbances have been the basis for the vast majority of man-machine systems analyses and have also received the lion's share of experimental effort.

The most important class of situations in closed-loop control of aircraft are compensatory tasks in which the pilot acts on displayed error quantities **e**, between desired command inputs, **i**, and comparable vehicle output motions, **m**, to produce control actions, **c**. This class is illustrated in Fig. 2. In this block diagram the dynamics of the equivalent controlled element and displays are described by a matrix of transfer functions, $\{Y_c(j\omega)\}$. The signals in this general block diagram, **i**, **e**, **c**, and **m**, as well as the remnant, $\mathbf{n}_e$ (considered as a quantity injected at the pilot's input) are all, in general, vector quantities. Finally, the transfer characteristics of the pilot are represented by the matrix of quasi-linear describing functions, $\{Y_p\}$. The describing functions and remnant depend explicitly on the *task variables*, as noted in the functional notation. (While an explicit functional dependence is not shown, the remnant and transfer characteristics are also functions of the operator-centered, procedural, and environmental variables.)

Fundamental Concepts in Pilot-Vehicle Analysis

So far, much of what has been said has emphasized how complex a beast the pilot is, and how difficult his actions are to describe in any way. This tends to be a ponderous approach, full of caveats; but to avoid glib generalities it is necessary to mention tedious details.

But, fundamentally, as applied to pilot-in-the-loop situations, the *basic concepts* are very simple. They derive from the three fundamental concepts listed in Fig. 3 which constitute the essential substance of pilot-in-the-loop systems analysis. The initial concept is that to accomplish guidance and control functions, as in flying approaches, intercepts, weapon delivery maneuvers, etc., the human pilot sets up a variety of closed loops around the airplane which, by itself, could not otherwise accomplish such tasks. To be satisfactory, these closed-loop systems have to behave in a suitable fashion: although animate and inanimate components are interacting, the over-all system must share certain of the qualitative dynamic features of "good" closed-loop systems of a solely inanimate nature. As the adaptive means to accomplish this end, the pilot must make up for any dynamic deficiencies of the effective controlled element as a whole by appropriate adjustments of his dynamic properties. There is a cost to this pilot adjustment: in workload-induced stress, in concentration of the pilot's faculties, and in reduced potential for coping with the unexpected. The measures of the cost are pilot commentary and pilot rating, as well as other workload-sensitive physical and psychophysiological measures.

Development Chronology of Pilot-in-the-Loop Analysis

The existing theory of pilot-vehicle analysis stands on four legs of past and ongoing research:

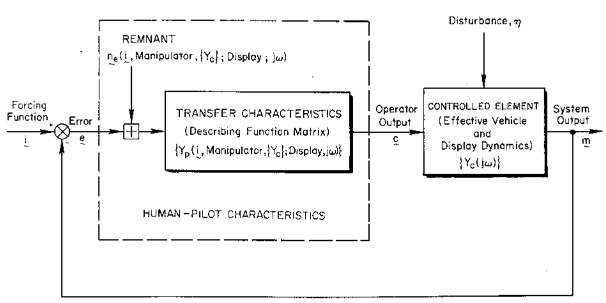

Fig. 2. Quasi-linear paradigm for the human pilot.

1) The experimental determination of human pilot dynamic characteristics for a wide variety of situations and conditions.

2) The evolution of mathematical models and manipulative rules which subsume the experimental data and can be used for predictions in feedback system analyses.

3) The experimental determination of relationships between pilot and total system properties and the cost of attaining these properties in terms of workload, reduced potential for graceful degradation and coping with the unexpected, etc. In other words, the relationships between the pilot-vehicle situation and the objective and subjective pilot assessments.

4) The combination of pilot dynamic and equivalent aircraft mathematical models to treat particular problems.

The fourth leg is a massive subject in itself, and will not be covered further here. Discussion of the other three will be the major content of the rest of the paper.

The pioneer in human operator dynamic measurements was Arnold Tustin in England, during World War II. Tustin introduced the concept of describing function and remnant measures in general and applied this concept to actual human operations. In reporting on his studies of manual control of a power-driven gun[3,4]:

> "The object of the series of tests was to investigate the nature of the layer's response in a number of particular cases and to attempt to find the laws of relationships of movement to error. In particular, it was hoped that this relationships might be found (within the range of practical requirements) to be approximately linear and so permit the well developed theory of 'linear servomechanisms' to be applied to manual control in the same way as it is applied to automatic following."

Also during the Second World War, and independently of Tustin, A. Sobczyk and R. S. Phillips at the MIT Radiation Laboratory[5] and H. K. Weiss[6,7] at Aberdeen presumed quasi-linear operation in a series of studies on aided tracking of guns.

After the war these seminal efforts, and the hope for a more rational approach to the design of aircraft, led Leo Chattler of the Bureau of Aeronautics and Charles Westbrook of the Air Force Aircraft Laboratory to sponsor some small-scale research efforts aimed at determining the dynamic characteristics of human pilots. For the Navy, the Goodyear group of Ray Meade, Nicholas Diamontides, and A. J. Cacioppa, headed by Robert Mayne, developed excellent analog computer representations for pilots for two specific task-variable situations.[8-11] The Air Force activity at Franklin Institute,[12,16] Princeton University,[13-15] Control Specialists Inc.,[13,16] and later Systems Technology Inc. chose to exploit cross-correlation and cross-spectral techniques to the same end. Parallel university research was underway at MIT with a remarkable Master's thesis by Lindsey Russell,[17] and a later doctoral dissertation by Jerome Elkind.[18]

The end of the pioneering era can be conveniently put with the publication of *Dynamic Response of Human Operators*[16] in October, 1957. This volume codified and correlated the available human response data, developed predictive models compatible with these data, and prescribed preferred forms for the operator which permitted specification of ideal characteristics for the controlled element associated with the man in the manual control system.

Since 1957 a very large number of measurements have been made for single-loop systems of all kinds. Using more and more refined measurement and data reduction techniques, many organizations and individuals have contributed, notably NASA/Ames and Langley; Cornell Aeronautical Laboratory; Bolt, Beranek, and Newman; Systems Technology Inc.; MIT's Manned Vehicle Laboratory, etc.

For Guidance and Control:
- Pilot Sets-up and Closes Loops

For Satisfactory Pilot-Aircraft System:
- Dynamic Properties Similar to Good Inanimate System
  - Pilot Offsets Aircraft Dynamic Deficiencies

Cost to the Pilot:
- Workload-Induced Stress
- Concentration of Pilot Faculties
- Reduced Potential for Handling Unexpected Events

Fig. 3 Fundamental concepts of pilot-in-the-loop analysis.

Going from single-loop to multiloop situations is a major step. The first studied were multimodality experiments in which a number of fundamental dynamic response measurements were made in aircraft and moving-base simulators to determine the effects of linear and rotary motion cues on the pilot's dynamics. Ordinarily, these have compared fixed versus moving-base situations on the basis of effective visual input pilot describing functions. In two or three instances it has been possible to uniquely separate the motion and visual transfer characteristics by using independent forcing functions. Significant experimental contributions have been made by NASA/Ames, STI, Cornell, and the Manned Vehicle Laboratory, among others.

Because measurement of unique pilot describing functions in multiloop systems is difficult, less than half a dozen experimental series pertinent to aircraft have been carried out. Although the available data form a solid data base for conventional aircraft control, they are a far cry from what is needed. This is one of the most important and difficult areas in current research.

The experimental data alluded to in broad terms above have been the basis for development of mathematical models and manipulative rules which can be used for prediction purposes. Some of these models will be described below. They will be presented in two stages. First, an elaborate and substantially complete quasi-linear model for human pilot operation in single-loop systems will be presented. This model comprises an adjustable adaptive describing function form which is relatively closely connected to physiological structure, a remnant or pilot-induced noise, and empirical correlations of pilot rating with appropriate features of the pilot model. The second model presented is an extension of the single-loop model to multiloop situations. The nature of multiloop manual control, the adjustment of the multiloop structure, and modifications to remnant and pilot rating are described. The multiloop model has several variants, depending on the nature of its perceptual stages in a particular instance or, in plain words, depending on how much scanning is involved. Some features and adjustment rules for these multiloop models are quite new, as we are just now assimilating the results of the latest multiloop measurement programs.

Single-Loop, Full-Attention Tracking Model—The Compleat Human Pilot

Modeling is well advanced to describe, interpret, and rationalize the enormous number of measurements since 1944. An overview which shows the current precision attainable for single-loop situations is presented graphically in Fig. 4. Here the controlled element dynamics are shown in one block, with all of the details being reserved for the pilot.

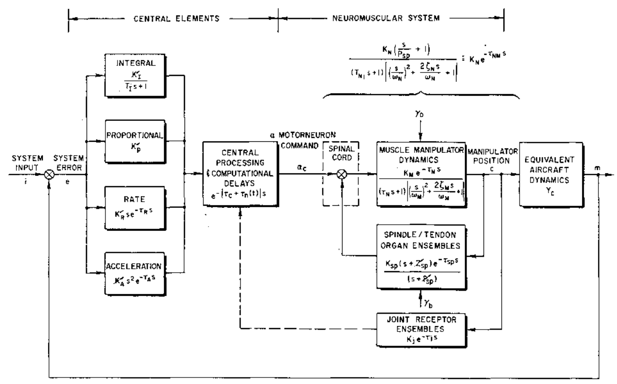

Fig. 4 The complete human pilot.

Starting on the pilot's right, we have the neuromuscular system. The one shown in the figure is a relatively complete description of the pilot's actuation dynamics. The entities called out, such as the muscle manipulator dynamics and spindle/tendon organ ensembles, have many demonstrated direct connections with actual neurological structure. Consequently, this portion of the model can be used for both behavioral and physiological descriptions. The degree of complexity shown is sometimes needed for the study of artificial feel systems, arm-bobweight effects, primary control system nonlinearities, etc. For other aspects of pilot-vehicle analysis problems, the neuromuscular dynamics are so high in frequency as to be relatively unimportant in their details. For these cases, a pure time delay, τ_{NM}, or a first-order lag can be used as a low-frequency approximation.

Turn now to the central and input elements on the pilot's left. As shown there, the pilot can develop a neuromuscular system input command which is the summation of a lag, proportional, lead, or double-lead function of his input command. The integral and proportional channels have a basic time delay, τ_c, associated with them. The higher derivative channels have additional incremental delays. These incremental time delays constitute the *dynamic cost of* pilot *lead generation.* They are about 1/5 sec for rate (τ_R) and greater than 1/2 sec for the acceleration channel (τ_A). For full-attention control, these incremental latencies are by no means insignificant. For instance, with controlled element dynamics which require utilization of the rate channel, the total system bandwidth may be only 70% of that attainable when only the proportional and integral channels are needed. A far greater penalty is present when the acceleration channel is required. Because of these important consequences on detailed performance of the pilot-vehicle system, any pilot model considered for use should contain the incremental time delay or a reasonable situation-specific approximation thereto.

The channel gains and the time constant, T_I, are all shown as variable quantities. Their adjustment is, to a first approximation, remarkably simple. In essence, they take on values such that the "crossover model" applies. What this means is that the pilot adjusts his net equalization such that the slope of the open-loop amplitude ratio is close to -20 dB/decade in the region of crossover frequencies (Fig. 5). The effective time delay, τ_e, is a low-frequency approximation to all the high-frequency lags in the system, including those due to the controlled element dynamics and to transport delays and high-frequency neuromuscular dynamics of the pilot.

At frequencies much less than or much greater than the crossover frequencies, the crossover model is neither appropriate nor accurate. When estimates for these frequency regions are needed, additional factors must be considered. These are cataloged in Refs. 19–21.

In the generalized block diagram of Fig. 2 the remnant was shown injected at the input to the transfer characteristic matrix. In recent years much remnant data for a wide variety of display conditions has been gathered. With adequate manipulators (i.e., those which do not induce a sinusoidal-like dither on the part of the pilot to effectively linearize control system nonlinearities[11,22]), the remnant has been shown to have a continuous power spectral density.[19] Although in principle there are many possible sources for the remnant, a step-by-step process of exhaustion eliminates most of them as major contenders. The principal source is now believed to be fluctuation in the pilot's effective time delay, as shown in Fig. 4 by the $\tau_n(t)$. This can be considered as a random change in phase, akin to a random frequency modulation; slight variations of sampling rate in a sampled data system; or whatever. When one is interested primarily in power spectral densities, or their time domain covariance function equivalents and the quantities derivable therefrom, the effect of any remnant source associated with the transfer characteristic can be modeled as an injected noise. Then, because any transfer characteristic nonlinearity or time variation will have an effect which is a function of the input amplitude, the remnant spectra arising therefrom tend to be more uniform at the pilot's input point. They are, therefore, most conveniently inserted at this point and are often referred to, accordingly, as "observation noise." Using the remnant as an inserted noise source is, as noted, adequate for calculations of mean-squared error and other quantities which can be derived from second-order statistics of the signals. If, however, finer-grained detail is needed, such as the probability distributions of signal amplitudes throughout the man-machine system, then more attention has to be paid to the actual remnant-generating process.

For single-loop systems an approximation to the remnant form, Φ_{nn_e}, when reflected to the pilot's input is given as[23]

$$\frac{\Phi_{nn_e}}{\sigma_e^2} \doteq \frac{(0.1 \text{ to } 0.5)}{(\omega^2 + 3^2)} \quad \text{when integral and proportional channels are used}$$

$$\frac{\Phi_{nn_e}}{\sigma_e^2} \doteq \frac{(0.1 \text{ to } 0.5)}{(\omega^2 + 1)} \quad \text{when the rate channel is used} \tag{1}$$

As demonstrated in Fig. 6 these analytical forms bound most of the available data. Note that the remnant is smaller, although somewhat more broadband, when low-frequency lead is not required of the pilot. Thus, another penalty for low-frequency lead generation is seen to be an increased remnant. The high-frequency asymptotes for both no-lead and high-lead situations is common. Consequently, the remnant increase when lead equalization is necessary is subsumed here primarily by the reduction in break frequency.

As already explained, because the kind of remnant described scales with signal variance, it clearly derives from some signal conditioning operations within the pilot such as the time-varying time delay mentioned previously. Accordingly, this component of remnant is a "processing noise." Later, another remnant component due to scanning will be introduced, which adds to the processing noise in multiloop situations.

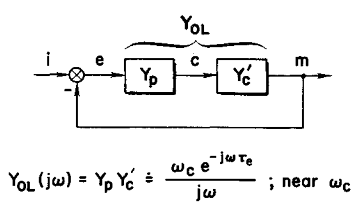

Fig. 5 Crossover model.

If remnant were totally of a processing noise variety, it would disappear when no forcing function or disturbance is present. There is a great deal of evidence, however,[24] that some remnant remains. This is wideband and independent of the signal variance. This "residual remnant" is the "motor" which keeps the signals throughout the loop fluctuating in the absence of any external driving source.

This finishes our quick review of the dynamic entities of the pilot model for single-loop situations. Next, we will turn to the question of workload, system assessment, and pilot rating. Although the answers we will ultimately give for single-loop systems in general are relatively simply stated, the subject itself is more complex. Consequently, we will treat this in a separate article, which follows directly below.

Pilot Rating, Workload, and Pilot Dynamics for Single-Loop Situations

To develop closed-loop analysis procedures which permit the assessment of flying qualities, system accuracy, etc., as quantities to be traded off with pilot dynamics and workload requires some generalized criteria. These should cover, as a minimum; measures of mission performance, effects of control augmentation systems, effects of aircraft dynamics, and, pilot workload. These are the kinds of factors which are taken into account by a skilled test pilot in providing a pilot rating using, for example, the Cooper-Harper Scale.[25] A general form of rating functional which explicitly contains some, and implicitly contains all, of the desired features is given by

$$R = R\Big[\overbrace{\underbrace{\dot{\lambda}_i \overline{q_i^2}}_{\substack{\text{Dominant aircraft}\\ \text{motion quantities}\\ \text{and task measures}}}}^{\substack{\text{Mission/task}\\ \text{performance}}};\ \overbrace{\underbrace{\overline{\sigma_j^2}}_{\substack{\text{Pilot activity}\\ \text{(scale of}\\ \text{pilot effort)}}};\ \underbrace{\frac{d\,|Y_p|_{dB}}{d\mu}\bigg|_{\mu_{1_k}}}_{\substack{\text{Pilot equalization}\\ \text{(dynamic quality}\\ \text{of pilot effort)}}}}^{\text{Pilot workload}};\ldots\Big]_{i,j,k} \qquad (2)$$

As displayed in Eq. (2) the functional form is general enough to include the existing[26-30] approaches to quantitative flying qualities rating criteria functions. The key closed-loop system quantities in the rating functional are measures of mission and task performance. These are conveniently described by a set of dominant weighted aircraft motion deviations and total system accuracy or error indications.

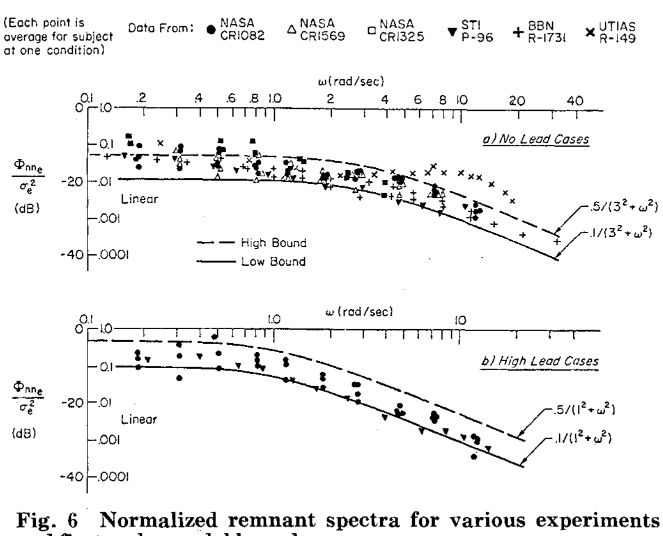

Fig. 6 Normalized remnant spectra for various experiments and first-order model bounds.

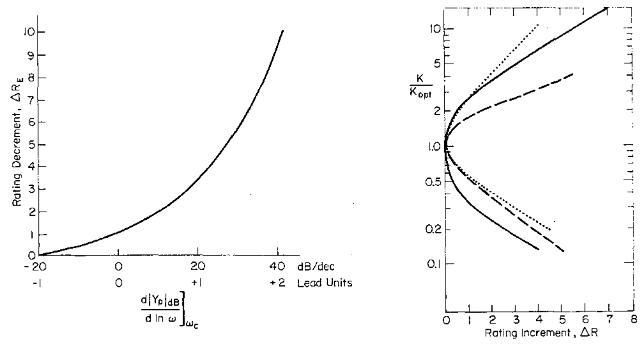

Fig. 7 Pilot rating decrements as functions of lead equalization and gain.

The pilot activity component of pilot effort, $\overline{\delta_j^2}$, is particularly dependent on the level of pilot gain. For a given gain, $\overline{\delta_j^2}$ increases directly with gust disturbance spectrum amplitude and remnant amplitude. Accordingly, both $\overline{\delta_j^2}$ and the $\overline{q_i^2}$ quantities will reflect turbulence and remnant levels.

The pilot equalization component of pilot workload is represented in Eq. (2) by the slope (in dB per octave or decade) of the pilot's amplitude ratio evaluated at a particular frequency (generally near crossover). This is by no means the only measure available to describe the dynamic quality of the pilot's effort. References 28–30, for example, use pilot lead time constants as measures; for particular situations with a sufficient data base, this may be a desirable alternative.

Unfortunately, there do not now exist for all closed-loop tasks sets of pilot rating, system performance, and pilot equalization data. Consequently, for many situations we must rely on available correlations which do not include quantities like the $\overline{q_i^2}$.

The pilot adapts to the vehicle and forcing function characteristics. He therefore reflects in his adapted describing function form many, if not all, of the vehicle dynamic characteristics and closed-loop pilot/vehicle system properties. Consequently, as a first approximation, a functional relationship can be set up between pilot ratings and the objective system factors in terms of the pilot dynamic characteristics alone. In this connection it has been found that the dominant rating-sensitive pilot parameters are the low-frequency lead equalization and the crossover gain. Typical relations of this nature are shown in Fig. 7. These can be used directly to estimate pilot rating once the pilot dynamics estimates are made.

The descriptive phrases listed under "Demands on the Pilot in Selected Tasks or Required Operation" in the Cooper-Harper Scale (Fig. 8) directly parallel the correlations with pilot lead equalization. There is also a strong connotation of increasing pilot effort and workload in the scale phrases. But, workload is difficult to define and, consequently, to quantify. In the spirit of offering a general definition which can be measured and predicted, it has been suggested[31] that workload margin be defined as the ability (or capacity) to accomplish additional (expected or unexpected) tasks. For example, the pilot opinion rating scale satisfies this definition up to its "uncontrollable" limit point. Furthermore, a number of auxiliary tasks, the decrements in scores on which give an index of demand on the primary task, will also satisfy this definition of workload. One particular measure has, at the moment, very great promise in integrating many of the measures into one basic context. This is *excess control capacity,* a major connector with pilot rating and main task effective time delay.

The notion that among the causal factors of pilot rating are the pilot's attempts to maintain performance by work-

AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair — Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Fig. 8 Cooper-Harper handling qualities rating scale.

ing harder to control in spite of the increasing difficulty is supported by an experiment which measured a parameter uniquely related to excess control capacity.[27] A secondary subcritical tracking task was used to load the pilot so that his performance on the primary task began to deteriorate. A block diagram of these tasks is shown in Fig. 9. The difficulty of the secondary task was made proportional to primary task performance. Thus, when the pilot was keeping primary task error performance less than a criterion value, the secondary task difficulty was automatically increased by increasing the rate of divergence of the secondary instability. Conversely, when the pilot was so busy with the secondary task that primary error was larger than the criterion value, the secondary task difficulty automatically decreased. The final stationary level of secondary difficulty was determined by the sensitivity of the primary task performance to loading. The final "score" is λ_s, the stationary value of the secondary unstable pole (λ) in rad/sec. The scores obtained from this cross-coupled secondary task represent its degree of difficulty; consequently, they also represent the "degree of ease" of the primary task or the excess control capacity available with respect to the primary task.

The achievement of the critical limiting score in the cross-coupled secondary task indicates a condition of

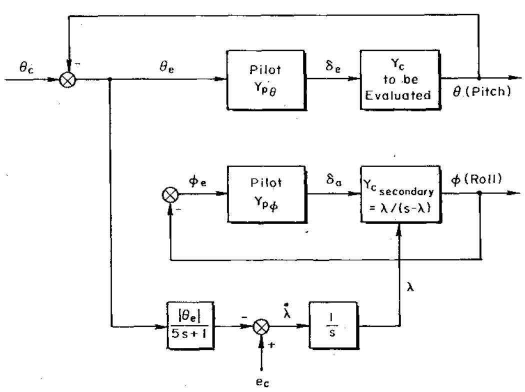

Fig. 9 Single-loop primary task with secondary cross-coupled loading task.

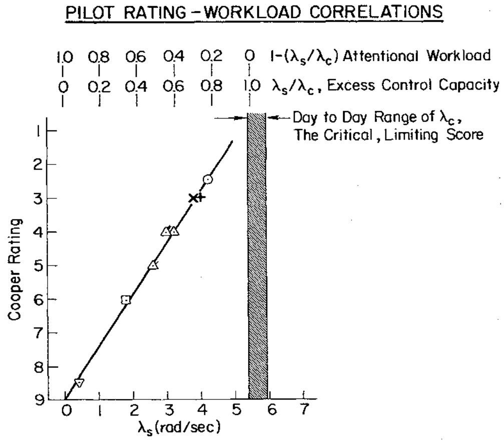

Fig. 10 Subjective pilot rating versus first-order cross-coupled instability score.

maximum available excess control capacity. We speak of the secondary task as a "critical" task in this limiting case. The critical task provides a divergent controlled element of a form that tightly constrains the allowable pilot equalization near the region of gain crossover. This property of the critical task leaves the pilot's effective time delay, τ_e, as the sole determinant of system stability. When the divergence is gradually increased until control is lost on the divergence, this "critical" divergence time constant is a measure of τ_e (Ref. 24). Thus, any activity by the pilot which demands an increase in τ_e on the *whole* task can be expected to prevent him from achieving his critical limiting score on the cross-coupled secondary task.

Secondary scores obtained for a variety of primary controlled elements are presented in Ref. 27. Figure 10 shows how the scores for the best gain configurations of each controlled element compare with the Cooper ratings. Even the subcritical task itself (the inverted triangle) in the role of the primary task, which has been a notable culprit in other correlations, seems to be correlated linearly with the other data. In Fig. 10 a score $\lambda_s = 0$ corresponds to 100% of the pilot's attention being devoted to the primary task or *no* excess control capacity, whereas a limiting score ($\lambda_s \doteq 5.5$) means that no attention is required to maintain primary task performance or that *100%* excess control capacity is available.

Multiloop Pilot Model for Tracking Situations

Fundamentally, there are three inspirations for multiloop control. The first is a desire to exert control over more than one quantity—in general, this requires one point of control application per control variable as well as meeting controllability and observability limitations.

The second reason is the use of auxiliary quantities as feedback in lieu of series compensation of primary quantities. Common examples of parallel (feedback) equalization are the use of pitch attitude (instead of altitude rate) to supply path damping in an altitude control system, and bank angle (instead of heading rate) to provide path damping for a heading control system. Often, the auxiliary feedback will have advantages in other respects. For instance, it may provide a more stable feedback for other than the primary modes considered, may be easier to instrument, may suffer less from noise contamination, or may be itself a suitable outer-loop feedback for some flight control system mode. Furthermore, for piloted control systems, the auxiliary feedback in lieu of series compensation can be profoundly important. This is perhaps best appreciated by recalling that pilot generation of lead equalization incurs penalties in incremental time delay, increased remnant, decreased system performance, increased pilot workload, and poorer pilot ratings.

The third reason for multiloop control is to achieve coupling or decoupling purposes. This is a modification of the effective controlled element transfer function numerators by auxiliary control from another control point.

Because this list of inspirations for multiloop control is particularly favorable for manual control, piloted situations may more often be multiloop than corresponding automatic conditions.

The key to multiloop pilot models is the first fundamental concept of pilot-vehicle analysis: that the pilot constructs feedback loops about the effective controlled element. The feedback quantities available to him for possible use consist of those; directly sensed within the general visual field, observable via visual displays, and directly sensed using modalities other than vision. Quantities which can be perceived from the full visual field will show no scanning penalties whereas those which require instrument scan or modification of the fixation point will introduce decrements in some features. These will be described subsequently.

The feedback quantities actually selected by the pilot will be those necessary to satisfy the guidance and control needs and certain pilot-centered requirements. The guidance and control needs are situation-specific. Although they often involve an outer loop with possible subsidiary inner loop and other axis closures as needed to make the principal feedbacks work, the same considerations apply for manual control as for automatic—that is, guidance and control requirements are essentially independent of whether the controller is animate or inanimate. This is such a vast subject by itself that no more can be said here. Examples of the development of guidance and control needs are given in Refs. 32–34.

The pilot-centered requirements are central to the manual control (as opposed to the general control) problem. These characteristics must be discovered by experiment, although theoretical constructs are useful for rationalization and inspiration. Unfortunately, as already remarked, because of the instrumental, measurement, and analytical difficulties inherent in finding unique pilot describing functions in multiloop systems, less than half a dozen experimental series pertinent to aircraft have been carried out.[35–37] Several other experimental series which assume forms for the pilot have been run by STI and others. These provide useful and, in some cases, definitive data even though the pilot dynamic characteristics are not uniquely defined. As a consequence of these studies, a series of adjustment rules similar to those for the single-loop model can be stated. These are as follows.

1) The multiloop situation with full visual field is similar to that shown in Fig. 4 with the perceptual portions of the central elements operating in parallel. Figure 4 is, in fact, appropriate for most multiloop full visual field situations if the signals i, e, c, and m are interpreted as vector quantities.

2) The feedback loops preferred are those which a) can be closed with minimum pilot equalization, b) require minimum scanning, and c) permit wide latitude in variation in the pilot's characteristics.

3) Where distinct inner- and outer-loop closures can be defined by ordering the bandwidths (e.g., the higher the bandwidth, the more inner the loop) a series multiloop structure applies.

4) The adjustment of the variable gains in each of the loops is, in general, similar to that which would be used by a skilled automatic flight control system designer who has available the same feedback entities. To a first approximation: a) The crossover model is directly applicable to many inner-loop closures. b) The crossover model also holds for the outer-loop of multiloop systems with the proviso that the effective controlled element transfer function include the effects of all the inner-loop closures.

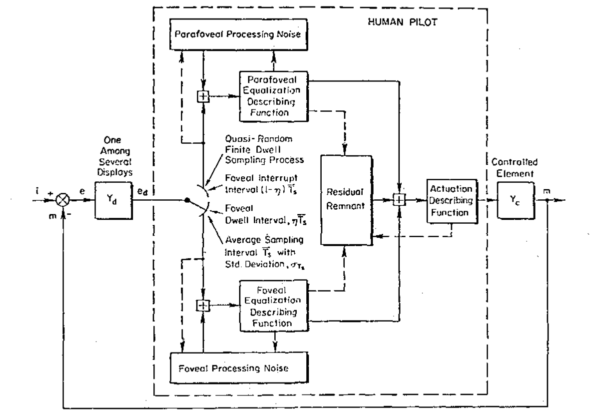

Fig. 11 "Switched gain" multiaxis scanning model for compensatory multiaxis tracking with one among several displays.

5) When scanning is not present, the remnant is primarily associated with the inner loop and is essentially the same as that for a single-loop system equivalent to the inner-loop alone.

Although scanning is avoided where possible, multiple fixations are sometimes required to sense the appropriate controlled element output quantities. The basic process of scanning during multiloop control tasks, sampling the fixated and parafoveal information, and reconstructing the scanned signal is very complex in detail. However, the essence of past work in this area[37–40] shows that in the process of extracting the feedback information from the displays: 1) A fairly stationary scanning strategy evolves for a given task and full field/instrument array. 2) The pilot's output control motions are much more continuous than the discrete sampling would seem to imply from the pure stimulus-response sequence. 3) The first-order effects of scanning are to reduce the pilot gain and increase remnant in the scanned channels.

The development of multiloop pilot models complete with scanning operations has now gone through several stages of theoretical and experimental operations. Many of the phenomena observed empirically can be modeled theoretically with two different multi-input, multi-output pilot model forms called, respectively, the "switched gain" model and the "reconstruction hold" model. The current version of these models is described in Ref. 41. We shall consider here the gist of the switched gain model only, since it is conceptually the simpler of the two.

This form of the model is termed switched gain because it incorporates a quasi-random finite dwell sampling or switching process between the pilot's foveal gain and his effective parafoveal gain on each of the several displays involved. Figure 11 illustrates the model with a block diagram. The foveal path is closed during the foveal dwell interval, and the parafoveal path is closed during the foveal interrupt interval. Each of these paths will, in general, exhibit different gains, equalization and effective time delays before the paths are combined in the higher neural centers to send a signal to the actuation describing function.

The conceptual block diagram in Fig. 11 can be remarkably simplified by recalling[42] that *any* quasi-randomly sampled and processed signal can be modeled by: 1) replacing the sampling or switching process by a continuous transmission path, and 2) adding an uncorrelated wide-band noise process which has a power spectral density proportional to the variance of the (displayed) signal before sampling. Since the quasi-random scanning process has a finite foveal dwell interval, the wide-band noise process will exhibit a low-pass power spectrum with a first-order break frequency which is inversely proportional to

SITUATION	CONTROL PROBLEM	CAUSES
Pilot-Induced Oscillations	Pitch (Single Loop)	Sensitivity; Bobweight/Feel Spring; Loss of Pilot Lag; Elevator Rate Limiting
	Roll (Single Loop)	ω_ϕ/ω_d Effect; Lateral Bobweight
Weapon Delivery	Heading Aim Wander (3 loops)	Loss of Roll Loop; Lateral-Directional Multiloop Cross Coupling
Carrier Landing	Path Control-Inability to arrest Rate of Sink (2 and 3 loops)	Dynamic Reversal in Path
Attitude Control	Pitch (Single Loop)	Improper Pilot/Stability Augmenter Matching

Fig. 12 Some past applications of pilot-vehicle system analyses: flight encountered problems.

the average foveal dwell interval.[38] The power spectral density of this foveal/parafoveal switched gain scanning remnant is given by

$$\Phi_{nn_s}(\omega) \doteq \frac{\bar{T}_s(1-\bar{\eta}_e)(1-\delta)\sigma^2}{\pi[1+(\omega T_{d_e}/2)^2]} \quad \left(\frac{\text{units}^2}{\text{rad/sec}}\right)$$

where

σ^2 = mean-squared value of the signal scanned
$\bar{T}_s$ = mean scanning interval
$\bar{\eta}_e$ = effective dwell fraction = $\bar{T}_{d_e}/\bar{T}_s$
$\bar{T}_{d_e}$ = effective dwell interval
δ = normalized lower bound on the domain of T_s: $T_0/\bar{T}_s$
$(1-\delta)$ = approximately $\sigma_{T_s}/\bar{T}_s$, the scanning variability ratio
σ_{T_s} = standard deviation in T_s

Measurements of this switched gain remnant in Ref. 40 have shown that it is *so predominant* compared with the other sources of remnant that the other sources cannot even be identified. This makes for great simplification of the remnant in the equivalent switched gain model.

Representation of the pilot's describing function in the switched gain model can also be greatly simplified. The foveal gain exceeds the parafoveal gain in all measurements which have been made.[40,43,44] This is probably because of the large displacement and increased rate thresholds in parafoveal perception by comparison with foveal perception. The switched gain model is represented simply by multiplying the ratio (Ω) of parafoveal gain to foveal gain by the interrupt fraction $(1-\eta)$ and adding the product to the dwell fraction (η) to obtain the *effective* dwell fraction, viz.,

$$\eta_e = 2 + \Omega(1-\eta) \tag{3}$$

where $\Omega = \omega_{c_p}/\omega_{c_f}$ = ratio of crossover gains for continuous parafoveal tracking relative to continuous foveal tracking ($0 < \Omega < 1$). The effective crossover gain for the equivalent switched gain model for one foveal/parafoveal channel is $\eta_e\omega_{c_f}$, where ω_{c_f} is the foveal crossover gain in continuous single-axis tracking of the same display and controlled element constrained by the same task variables.

There are no apparent phase penalties associated with switched gain scanning as long as parafoveal perception is not completely inhibited. Inhibition can occur either by requiring a multitude of different widely-separated fixations with a time constraint or by inducing "tunnel vision" on one or two displays. Even so, measurements reported in Ref. 40, where parafoveal perception was inhibited by blanking the parafoveally-viewed display, show only small effective time delay increments ($\Delta\tau_s$) on the order of 0.05 to 0.15 sec attributable to scanning as the parafoveal-to-foveal gain ratio (Ω) approached zero.

The switched gain model has been quite successful in modeling behavior on a main task in laboratory experiments with induced natural scanning between a primary tracking task and a secondary subcritical tracking task[40] and on foveal and parafoveally-viewed displays.[43,44]

SITUATION	ANALYSIS RESULTS
Basic Airframe and Primary Control System	Predict multiple, closed-loop pilot-vehicle system problem areas and assess possible solutions
Pilot/Stability Augmentation Tradeoffs	Candidate stability augmentation systems, pilot behavior and workload, system performance and compromises, reliability, redundancy, etc.
SAS Failure Effects	Pilot actions and resulting aircraft excursions
Competing Pilot Display Formats Manual Control AFCS Monitoring	Information requirements, scan patterns, workload, assessment factors and criteria
Flight Director	Command display laws, status information requirements, flight director/pilot/stability augmentation tradeoffs
Carrier Landing Aids	Optimum FLOLS control and stabilization
Categories II and III Landing System	Probability of approach success, decision "state windows", touchdown statistics, manual/automatic tradeoffs, guidance sampling
Energy-Trim Management	Simplified controls/displays

Fig. 13 Some past applications of pilot-vehicle-display system analyses: design.

SITUATION	ANALYSIS RESULTS
Pre-Experimental Analysis	Predict critical areas and parameters, guidance for experimental design, pilot briefing, questionnaire
Post-Experimental Analysis	Interpretation and generalization of results
Competing Piloting Techniques	Pilot control procedures, system performance and safety margin differences. Control system refinements to simplify piloting technique
Motion-Cue Simulation	Task-dependent motion sensitivity, optimum washout design

Fig. 14 Some past applications of pilot-vehicle-display system analysis: simulation.

Multiloop Pilot Rating Considerations

At present the most successful means of obtaining ratings for multiloop situations is based on excess control capacity concepts.[45] First, assume that the relationship between pilot rating and excess control capacity, $\lambda_n \equiv \lambda_s/\lambda_c$, given by Fig. 10 is applicable to each loop of a multiloop manual control system. Then for each such loop a pilot rating, R, can be estimated using the single-loop correlates previously discussed (Fig. 10) and an excess control capacity, λ_n, assigned accordingly.

Single-axis capacity, or attention, values can be combined to yield the combined axis value by a multiplication process, i.e., the multiaxis excess capacity, λ_{nm}, is given by the product of the excess capacities for the individual axes

$$\lambda_{n_m} = \prod^{m} \lambda_{n_i}$$

and for $R = A + B\lambda_n$ as a linear fit of the Fig. 10 data, the multiaxis rating R_m will be given by

$$R_m = A + B\lambda_{n_m} = A + B \prod^{m} \lambda_{n_i} = A + B \prod^{m} \left(\frac{R_i - A}{B}\right)$$

$$R_m = A + \frac{1}{B^m - 1} \prod^{m} (R_i - A)$$

Combined ratings are always greater than (or equal to) individual ratings, since combined λ_n's are always less than any individual λ_n. Also, the maximum value of R_m never exceeds A, i.e., for large $R_i < A$, $\Pi^m(R - A) \rightarrow 0$.

The logical value for A is 10.0 and B is determined, using the empirical data, to be equal to -8.3. This results in a good over-all fit to all the available multiloop rating data.[45]

Application Summary

Since its first rudimentary applications in the early 1950's, man-in-the-loop analysis has grown exponentially to the point where it is now commonly used to consider a very wide range of problems. Perhaps more important is its establishment as a mode of fundamental thinking on the part of technical practitioners in the handling quality field and in its increasing use in aeronautical engineering curricula. To illustrate some of the applications, they have been divided into three categories for convenience and presented in outline form in Figs. 12–14.

1) *Flight Test Problems* (Fig. 12): The first category is also the smallest because it lists problems initially encountered far down the line in an aircraft development, i.e., in the flight test phase. In all of these cases the application of the pilot-vehicle analysis procedures led to a delineation of the cause of the troubles and further application of the procedure led to solutions.

2) *Design Problems* (Fig. 13): By far the most widespread use of any good predictive technique is in the design phase. Here, specific instances are too numerous to list, so more general classifications are used in Fig. 13.

3) *Simulation Problems* (Fig. 14). In simulation experiments the theory is ideal for program planning before the experiment and data interpretation and generalization afterwards. Like all good theories it has the supreme attribute of focusing the experimental effort on critical issues. And again, like all good theories, it has the characteristic which permits the fitting of experimental data into a broader, more general context. These generalizations not only describe the use in simulation problems but also serve as a suitable windup for the entire discussion.

A cross section of references on specific applications from which most of the items were drawn is given in Ref. 46.

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