CLOSED LOOP FLYING QUALITIES CRITERIA

Frank L. George

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Air Force Flight Dynamics Laboratory
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Air Force Systems Command
Wright-Patterson AFB, Ohio

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SUMMARY

This paper addresses the subject of closed loop, or pilot-in-the-loop, flying qualities requirements for military airplanes. The need for such criteria and their potential advantages are discussed. A definition of the term closed loop criteria, as used in this paper, is given. Various methods for developing closed loop criteria are reviewed and examples of such criteria are discussed. The strengths and weaknesses of this approach to flying qualities criteria are pointed out along with potential research areas.

THE NEED FOR CLOSED LOOP CRITERIA

Consider the following trends in military aircraft, particularly tactical and strategic vehicles:

large flight/performance envelopes
highly complex systems
high cost systems

These factors dictate that the military service receive the greatest possible mission effectiveness and survivability from these piloted aircraft systems.

Because of their large operating envelopes, these military airplanes must perform efficiently and maintain a good pilot-airplane interface over a wide variety of flight conditions. Current design methods and anticipated mechanization concepts to achieve these goals lead to configurations that include complex stability and control augmentation as an essential element. The resulting dynamic system, shown in Figure 1, may exhibit significantly different responses to various stimuli such as external disturbances, mode changes or failures, as opposed to deliberate commands.

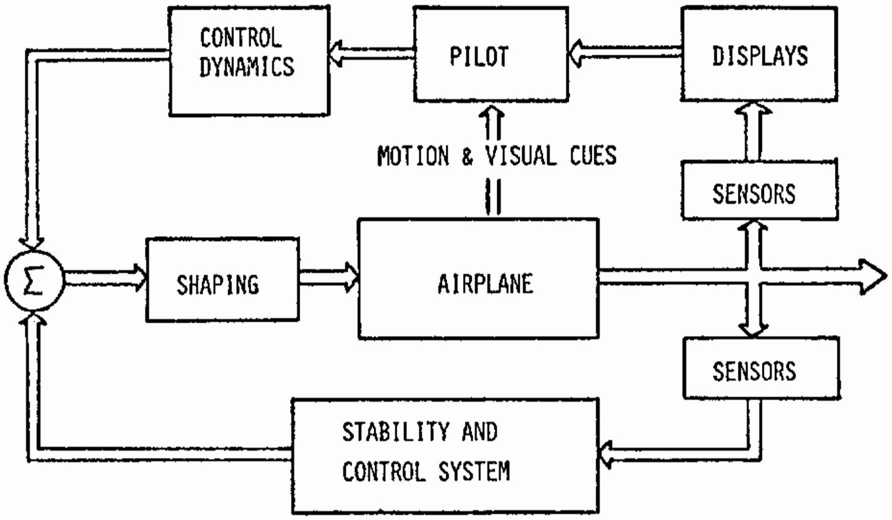


FIGURE 1. PILOT-AIRPLANE CLOSED LOOP SYSTEM

Note that Figure 1 should be viewed as a generic system diagram where, for example, the "stability and control" system block may be a complex subsystem containing automatic control functions as well as stability augmentation.

In addition to the variable dynamics described above, it is desirable to tailor the system dynamic characteristics to enhance the performance of various mission tasks. Thus, for the reasons summarized below, it becomes essential to have closed loop, or pilot-in-the-loop, flying qualities criteria:

- potentially large differences between open loop and closed loop dynamics

- desire to be consistent with military emphasis on improved mission effectiveness

- desire to be consistent with the design philosophy of task-oriented multimode controls.

A DEFINITION OF CLOSED LOOP FLYING QUALITIES

As discussed in the previous section, closed loop flying qualities deals with the dynamic characteristics of the total pilot-in-the-loop system of Figure 1. This certainly is not a new idea. For example, Reference 1 says much the same thing in contrasting open loop and closed loop flying qualities as shown in Figure 2.

OPEN LOOP:

- CHARACTERISTICS RELATED TO UNATTENDED OPERATION - PREDOMINANTLY THE STABILITY AND RESPONSE TO STIMULI OF THE [AUGMENTED] AIRCRAFT ALONE

- CHARACTERISTICS RELATED TO THE BASIC ABILITY OF THE AIRCRAFT TO EXECUTE MISSION-RELATED OR EMERGENCY MANEUVERS ASSUMING AN IDEAL PROGRAMMED CONTROLLER - PREDOMINANTLY THE LIMITING (MAXIMUM) CONTROL AND STEADY-STATE RESPONSE CHARACTERISTICS

CLOSED LOOP:

- CHARACTERISTICS RELATED TO CLOSED LOOP CONTROL - PRIMARILY THOSE DYNAMICS INVOLVED WITH THE PILOT/AIRCRAFT INTERACTION IN A FEEDBACK CONTROL SITUATION

FIGURE 2. OPEN LOOP vs CLOSED LOOP FLYING QUALITIES

Hence, the subject of this paper can be defined in the following deceptively simple-appearing statement.

> Closed loop flying qualities consist of those combined pilot-vehicle system characteristics that impact the satisfactory performance of precise pilot-in-the-loop tasks.

The true complexity of this subject is reflected by the considerable amount of research, and technical documentation which addresses the topic. References 1 through 6 are a small sample of the pilot-in-the-loop flying quality theories that have been proposed.

CLOSED LOOP FLYING QUALITIES CRITERIA OBJECTIVES

As with the definition above, the fundamental goal of closed loop flying qualities analysis and requirements is deceptively easy to state. That is:

> We must develop the capability to understand what the pilot needs to know and what he needs to do in order to complete a task - and relate that knowledge in some quantitative sense to system design parameters.

Figure 3 serves to illustrate this goal as well as some of the complex interactions and dynamic effects that complicate the situation.

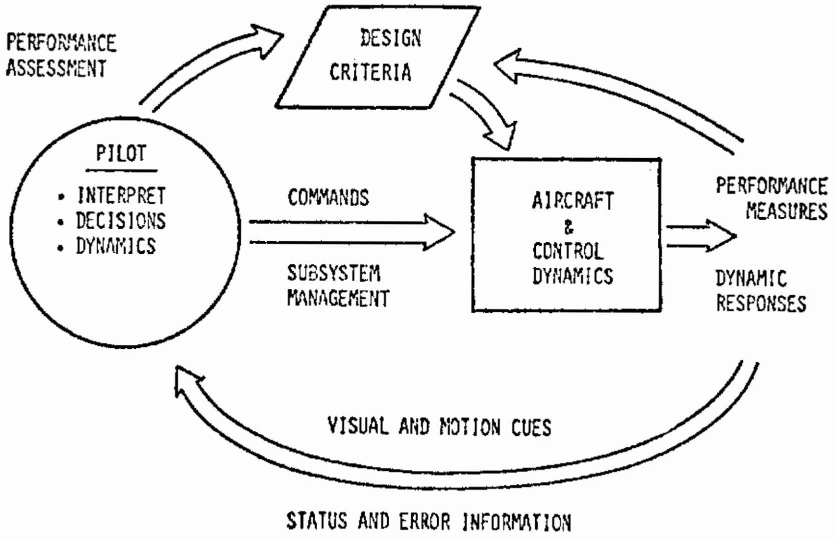


FIGURE 3. CLOSED LOOP FLYING QUALITIES ANALYSIS PROBLEM

For example, the pilot is recognized to be a complex dynamic element of the closed loop system, and considerable attention has been given to analytically modeling his dynamics when acting as a tracking control element. References 7-10 describe the two most widely used approaches to modeling and analysis of the pilot as a control element. However, it is necessary to understand the pilot's total role in the closed loop system to develop adequate flying qualities criteria. This broader understanding, and associated modeling capability, is needed to help identify appropriate closed loop flying qualities metrics.

One example of broadening our understanding in the closed loop situation deals with the concept of control harmony. In the present requirements, harmony deals primarily with inter-axis consonance of controller characteristics. In the context of closed loop flying qualities criteria, the concept of harmony can be expanded to encompass the pilot's overall interface with the aircraft systems. This interface exists whether the pilot is performing as an active controller or as a monitor. Thus the pilot needs appropriate displays and cues for both actual and anticipated control actions.

It therefore becomes necessary to consider the pilot's anticipated role in the closed loop system when defining appropriate closed loop criteria. For example, if closed loop criteria are to be defined in terms of task performance measures, it must be recognized that significant differences in task performance can occur between manual and automatic control modes because of different parameters and control paths that may be employed. Hence, the primary and backup operating modes must be determined, and appropriate criteria provided for each.

To summarize, if the pilot and aircraft system are considered as coupled dynamic elements, then it is also appropriate to treat the design criteria as being dynamic in the sense that they should be tailored to the particular application. The nature of closed loop metrics and the form of criteria consistent with this philosophy are the topics of the next section.

APPROACHES TO CLOSED LOOP CRITERIA

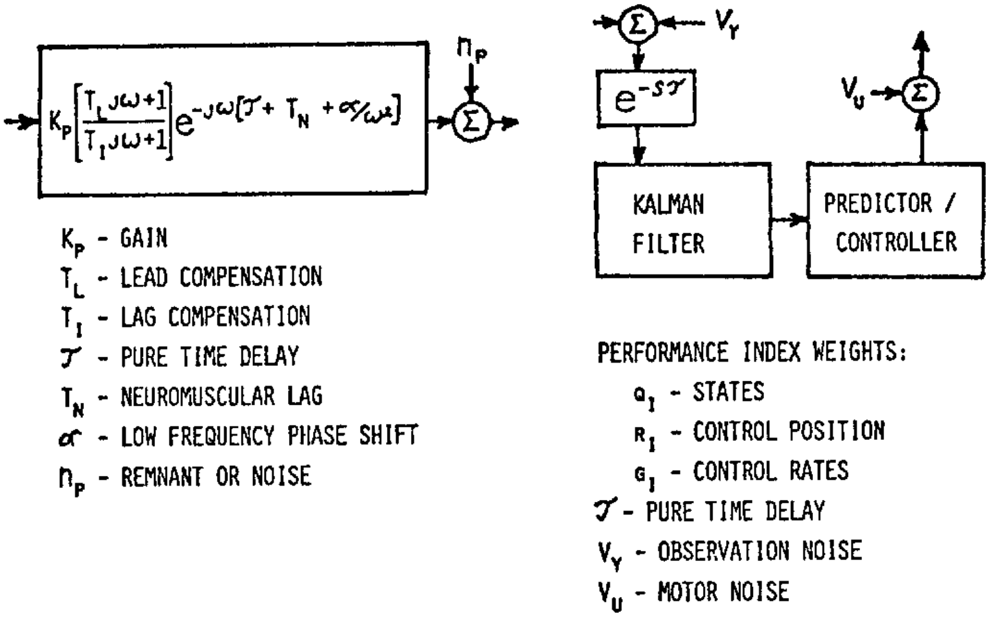
As a first step in developing new closed loop criteria, it is logical to review the present requirements, both to assess needs and to establish a baseline. MIL-F-8785B, Reference 11, contains some 31 paragraphs or subparagraphs in its four major requirements sections that could be construed to address closed loop flying qualities. These requirements address the following general areas:

control forces and feel in maneuvering flight,
nonlinearities and transient effects,
pilot-control-system dynamic stability (e.g. pilot induced oscillations).

The approach in these current requirements is to define airplane characteristics that will lead to an appropriate pilot interface. (An example is controller force and feel characteristics). One potential approach to future closed loop criteria would be to continue within the present framework. That is, establish numerical bounds on the airplane system characteristics, those already defined plus appropriate new ones, perhaps using an expanded task/flight phase grid structure. An advantage to this approach is, of course, that it builds on the familiarity of the present criteria. A disadvantage, however, is the reliance of many of these criteria on empirical data to establish numerical bounds. This reliance on empirical data limits the utility of the criteria in evaluating new designs that fall outside the current data base; it also makes criteria revision a potentially expensive and lengthy process due to the need for generating and validating new data. However, a more fundamental limitation of this approach is that the criteria do not directly address the effectiveness, or task performance, of the coupled pilot-in-the-loop system.

Most alternatives to the approach discussed above involve in some way the topics of pilot modeling and pilot-vehicle analysis. For example, criteria could be defined in terms of closed loop task performance such as landing accuracy or target tracking error. A design engineer would quite likely use some form of pilot-vehicle analysis for at least preliminary evaluation of proposed configurations against such criteria. An approach to criteria that involves pilot modeling more explicitly is to establish bounds on pilot control activity (including workload) to achieve desired closed loop task performance characteristics. The obvious question regarding these and similar approaches centers on the understanding of the pilot's function in the closed loop system and the ability to model his essential characteristics. As anyone involved with flying qualities knows, this question has been addressed in research and debate for many years. Two methods of analytically modeling the pilot have evolved that have been applied in a variety of situations with reasonable success. Figure 4 outlines the basic features of these two methods. References 12, 13, and 7 trace the evolution of the servo model while References 8,9, and 10 describe development of the optimal control model.

While the two pilot model approaches shown in Figure 4 look different, the fundamental assumptions and limitations are the same. That is, both assume the pilot acts in some optimal fashion and can be represented by a linear model. Also, both are limited in application - to closed loop, small amplitude tracking tasks. Within these limits, however, the models have been used with some success to analyze closed loop flying qualities problems and derive criteria. Examples of pilot-vehicle analysis applied to criteria development include Neal and Smith's pitch dynamic criterion described in Reference 14, the turn coordination requirement developed by Ashkenas, et. al. in Reference 15, and the pilot induced oscillation requirement proposed by Smith in Reference 16.



A) SERVO MODEL

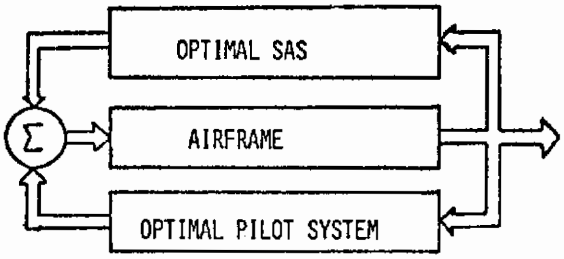
B) OPTIMAL CONTROL MODEL

FIGURE 4. PILOT MODELING APPROACHES

The common element of these three developments was the approach of defining criteria to achieve desirable closed loop response characteristics directly in terms of measurements of the system dynamic characteristics. The two following examples illustrate the potential of defining criteria in terms of closed loop task performance, as correlated with pilot opinion rating.

References 5 and 17 propose methods for analytically predicting Cooper-Harper Pilot Opinion Rating using pilot modeling techniques. Both references rely on the optimal control model, but propose different metrics to correlate the closed loop system characteristics with pilot rating. The metric in Reference 5 derives from the pilot model structure, while Reference 17 uses the optimal control performance index which includes both pilot control and closed loop response characteristics. It is generally accepted that the pilot's subjective Cooper-Harper rating of flying qualities is a function primarily of his workload (e.g. control activity) and task performance (e.g. observed closed loop errors). Hence, this approach admits the possibility of defining closed loop criteria very simply in terms of the pilot's assessment of task performance. Since Reference 18 has defined a relationship between Cooper-Harper rating and levels of flying qualities, this approach presents a viable alternative for evaluating pilot-vehicle system characteristics in those cases where other forms of definitive criteria are lacking, as discussed below.

Schmidt proposes an interesting synthesis method in Reference 19 which takes advantage of this conceptual approach. The synthesis procedure, illustrated in Figure 5, is summarized as follows.



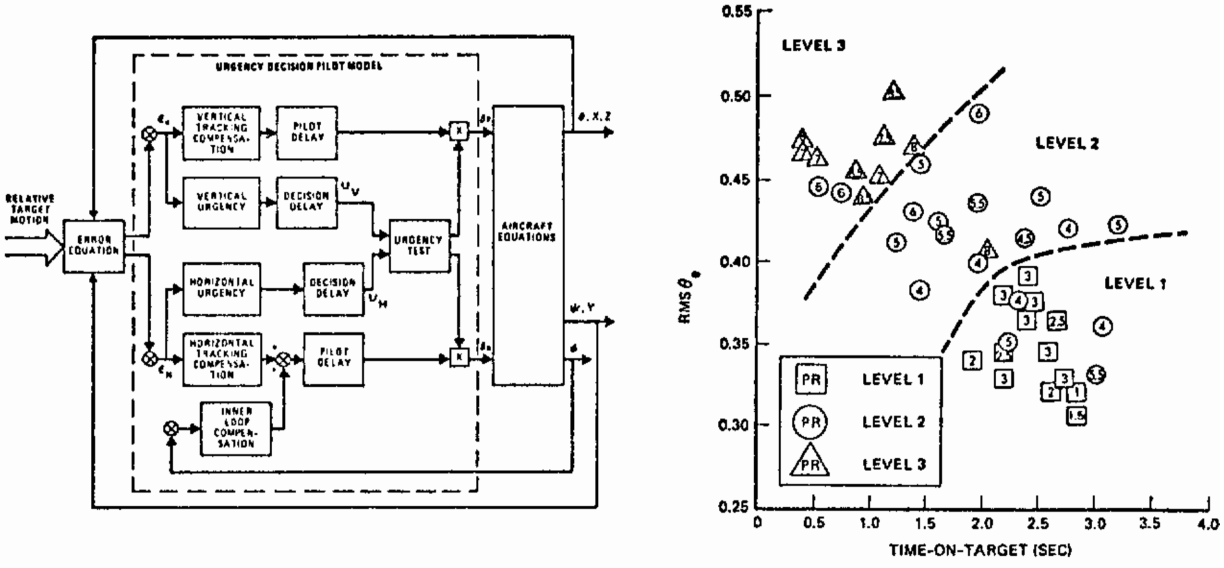
$$J = E\left\{\lim_{T\to\infty} \frac{1}{T}\int_0^T \left(Y'QY + U_p'RU_p + \dot{U}_p'G\dot{U}_p + U_s'FU_s\right)dt\right\}$$

$$\left.\begin{aligned}
&1)\quad A_p\Sigma + \Sigma A_p + W - \Sigma C_p' V_y^{-1} C_p \Sigma = 0\\
&2)\ -\begin{bmatrix} A & B \\ -G^{-1}K_{P_3} & -G^{-1}K_{P_4}\end{bmatrix}' K_S - K_S' \begin{bmatrix} A & B \\ -G^{-1}K_{P_3} & -G^{-1}K_{P_4}\end{bmatrix} - P\\
&\qquad\qquad + K_S' \begin{bmatrix} B \\ 0 \end{bmatrix} F^{-1} \begin{bmatrix} B' & 0 \end{bmatrix} K_S = \dot{K}_S
\end{aligned}\right\} \quad U = U_{P_{OPT}} + U_{S_{OPT}}$$

FIGURE 5. OPTIMAL CLOSED LOOP SYNTHESIS METHOD

An optimal control performance index, J, is defined which includes both manual and automatic control effort as well as closed loop responses. This leads to the solution of a pair of coupled Riccati equations to arrive at the optimal closed loop system. Applying this method as a design approach allows for direct evaluation of trade-offs between manual and automatic control workload in relation to closed loop dynamic characteristics. Furthermore, adjusting the pilot weighting parameters in Schmidt's performance index in accordance with the method of Reference 17 would permit a direct assessment of the resulting closed loop system flying qualities in terms of a predicted pilot-rating.

Onstott's approach to closed loop criteria in Reference 6 is similar to the above in that his results are in terms of closed loop task performance. However, he employs the classical servo pilot model as the basis for his pilot description. Also, the relationship between task performance and the pilot's evaluation of flying qualities is more direct. While Onstott's pilot modeling approach evolves from the classical single loop tracking model, it results in a nonlinear model with several unique features, as seen in Figure 6.



MULTIAXIS NONLINEAR MODEL

PROPOSED PRECISION TRACKING CRITERION

FIGURE 6. CLOSED LOOP TRACKING CRITERION

Most significant is the explicit modeling of the pilot's decision logic and control switching for multiaxis control. Provision is also made for modeling a side task for considering workload in connection with closed loop flying qualities. Figure 6 also contains a proposed closed loop flying qualities criterion developed analytically using the model. This criterion applies to a precisely defined closed loop task that involves both target acquisition and tracking. It is further defined to be a finite time (5 sec.) task in order to be more realistic. Note that very good correlation is shown between task performance measures and subjective flying qualities evaluation for a wide range of dynamics (Neal and Smith flight test configurations from Reference 14). This approach also appears to have potential for further exploitation.

CONCLUSIONS REGARDING CLOSED LOOP CRITERIA

Closed loop, or pilot-in-the-loop criteria, appear to be appropriate means for specifying military flying qualities requirements consistent with present philosophy and technology. A key element to success in developing closed loop criteria is our understanding of the dynamic pilot-vehicle system and our capability to properly model those aspects pertinent to flying qualities. We have a relatively good capability with regard to the airplane and automatic stability and control aspects. The pilot element is reasonably well understood for precision tracking tasks. However, the capability for handling more complex or higher order activities is not well in hand. The successful applications of current capability are encouraging, though, and may provide incentive to continue work on the more complex problem, as in Reference 20, for example.

It appears that no one approach can, or should, be chosen as "best" among the ones available. Rather, the advantages and limitations of each should be recognized, and the methods used accordingly. The present emphasis in the military on cost and mission effectiveness, however, would give preference to those methods and criteria that afford the designer the greatest latitude in making system tradeoffs to address these additional constraints. Optimal control theory methods potentially have great advantages in their ability to handle diverse constraints, but the problem of relating the abstract model parameters to physical system characteristics is formidable. This aspect of the optimal control approaches remains the most obvious area for additional research. In fact, the general area of closed loop flying quality metrics offers considerable opportunity for future research.

The planned change in the format of military systems-oriented specifications provides a special impetus to pursue the research topics outlined above. The new format will include a Mil-Prime Standard document and an accompanying Air Force Handbook. The Prime-Standard will contain general statements of requirements, which will then be tailored for each application - including insertion of quantitative requirements - in accordance with the Handbook guidance. The Handbook will contain supporting data and will afford an opportunity to present alternative approaches for design to the requirements and for verifying compliance. Such a presentation could include comparative discussion of alternative approaches.

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