Discrete Maneuver Pilot Models for Flying Qualities Evaluation

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A new approach to flying qualities specification and evaluation is presented which coordinates current research in the areas of pilot ratings, pilot-aircraft modeling techniques, and simulation and flight test procedures. A time domain pilot model is described which can model discontinuous and nonlinear pilot behavior in conjunction with completely general time-varying nonlinear aircraft models to simulate both discrete and continuous maneuvers. This pilot-aircraft model is applied to an existing set of in-flight simulation data, and calculates tracking error and time-on-target statistics for step target tracking that directly relate to the reported pilot comments and ratings.

Introduction

AS the control characteristics of advanced tactical aircraft depend increasingly less on the dynamics of the bare unaugmented airframe, the existing relations of handling qualities evaluation parameters to airframe dynamics become less reliable. Since most flying qualities evaluation and specification methods depend upon this correlation between airframe parameters and pilot ratings, there are now serious deficiencies in existing design criteria. MIL-F-8785B, Military Specification, Flying Qualities of Piloted Airplanes,[1] presents boundaries of acceptance in terms of such quantities as short period frequency and damping. These criteria have been obtained through operational experience with large numbers of past and current aircraft, and present values of airframe parameters that correlate with pilot ratings of 3.5 or better on a revised Cooper Harper scale for normal operation.

Since these criteria are no longer sufficient or comprehensive, there has been considerable research into 1) the nature of pilot ratings, 2) the dynamics of closed loop piloted flight, as predicted using dynamic models of pilot control compensation, and 3) innovative simulation and flight test procedures. There has been considerable success in these three areas. Pilot ratings deriving from different rating systems can now be related to one another, and the relation of ratings to certain performance measures has been demonstrated. Many of these piloted aircraft measures can now be reliably predicted using modern control theory, regarding the pilot as an element of the control system of the aircraft.[2] The ability to predict target tracking accuracy and attitude stabilization in turbulence,[3,4] for example, has been extended to pilot rating prediction methods by weighting performance with pilot or pilot model parameters. This has led to pilot rating data consistent with several flight test and flight simulation programs.[5]

On the other hand, flight test and flight simulation – both in-flight and ground-based – have not been subject to mathematical constraints that have limited the generality and scope of the analytical methods. Consequently, test methods have evolved along lines of discrete test maneuvers evaluated by measures that have not been readily computed by the use of analytic models.

It is unfortunate that these three areas of activity have not led to an integrated, consistent, and comprehensive approach to the evaluation and specification of piloted aircraft flying qualities. The problem is that pilot ratings and comments are difficult to relate to widely used frequency domain or optimal control pilot models. Furthermore, many flight test procedures, such as wind-up turns and step target tracking, have not been analyzed, owing to their nonlinear time-varying descriptions, which are not easily incorporated into pilot-aircraft models.

Pilot ratings and comments often refer to two basic kinds of evaluation: 1) How well can the aircraft perform? and 2) How hard was the task to carry out? Since these two questions are asked simultaneously by the Cooper Harper decision tree employed by the pilot in assigning a rating, performance and pilot workload are combined into a single scalar quantity, the rating. The pilot rating prediction formulas just mentioned weight normalized statistical performance, usually an rms tracking error, along with an assumed correlate of pilot workload, usually the pilot lead compensation constant. Although this method has correlated well with steady-state tracking data, the predictive and practical aspects of this approach have yet to be demonstrated, especially in view of the simplifications required in task descriptions and system models. The basic problem with these approaches is that pilot model parameters of lead, reserve attention as defined by additional task requirements on the pilot, or other identifiable pilot characteristics are difficult to relate to pilot comments. Furthermore, the limitation of pilot model analysis to steady-state statistics of a linearized pilot-aircraft model precludes analysis of discrete flight test maneuvers such as wind-up turns and step target tracking.

The objective of this paper is to present a simple method for coordinating these areas of flying qualities research through the use of time domain pilot-vehicle analysis, which can be used to model discrete maneuvers and fully general aircraft. This approach calculates tracking error and time-on-target statistics for step target tracking in a way that is directly related to both pilot ratings and comments. As an illustration of this technique, the definitive in-flight simulation study of longitudinal flying qualities, performed by Neal and Smith,[6] will be analyzed in terms of step target tracking.

Time Domain Pilot Model

To meet the requirements for design and development of advanced tactical aircraft, a methodology has been developed for predicting and evaluating closed loop piloted flying qualities. This method not only incorporates fully general, time-varying, nonlinear aircraft models, but also discontinuous and nonlinear pilot behavior that dominates in weapon delivery and terminal control problems. By adopting

Received July 15, 1977; revision received Nov. 21, 1977.

Index categories: Handling Qualities, Stability and Control.

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the method of digital simulation as a context for the pilot-aircraft model, this method can be readily employed with any aircraft models that may be available. It is particularly useful to use the pilot models in conjunction with large flight simulators by appending the pilot model to the simulator drive computer programs. In this way, exact comparison between the model and manned flight simulation can be made.

The idea of representing a pilot as a servoelement in order to investigate his control activity has been widely investigated from frequency domain as well as optimal control approaches. This has led to validated representations of pilot control compensation for steady-state tracking, primarily of single task problems.[2] Research has shown that models consisting of only pilot model gain K_p, error rate feedback lead T_L, and human transport time delay τ, as shown in Fig. 1 for a pitch angle stabilization in turbulence problem, can be used to predict tracking error to an accuracy of 10%.[4]

The general time domain pilot model is capable of great flexibility in aircraft description, task description, evaluation measures, pilot perception effects, pilot attention allocation, and time-varying pilot control logic. In particular, the investigation of air-to-air target tracking, where the target aircraft executes discrete maneuvers, requires these methods.[7] In this problem, the pilot model can employ initial control strategies that differ from the final precision tracking activity, where a finite fixed tracking time is specified. In this way, nonlinear performance measures, such as time-on-target defined by a gunsight pipper size, can be computed during the simulation of the pilot model-aircraft system. At the same time, these pilot models, and their use in conjunction with existing aircraft simulations, allow their routine use by control development and design organizations.

Pilot-Aircraft Analysis of Step Target Tracking

One of the most familiar and widely employed guides to longitudinal flying qualities is the data obtained by Neal and Smith of Cornell Aeronautical Laboratory during an in-flight simulation sponsored by the Air Force Flight Dynamics Laboratory in 1960.[6] The test matrix included variations in short-period frequency, damping, and control system parameters. Flight test evaluation included pitch angle tracking of both random and step function commands. The reported pilot ratings and comments cover stick forces, predictability of response, attitude control/tracking capability, normal acceleration control, effects of random disturbances, and instrument flight rules problems. Most pilot comments deal with initial response (predictability of response) or precision attitude tracking control (attitude control/tracking capability).

It is clear that the objectives of quick initial response and precise tracking, once the target is acquired, are to some degree opposed. If the pilot pulls toward the target too rapidly, unwanted overshoot and oscillation about the target may result. On the other hand, pulling too slowly to the target may lead to steady tracking, but with a penalty of unacceptably slow target acquisition. The ability to investigate this compromise, and predict how well it can be achieved for a given aircraft, is the primary advantage of using the time domain pilot model to investigate step target tracking.

Consider a target that suddenly appears above steady-state trim only in pitch for the tracking aircraft. The pilot sees the target and initiates a pull-up. At some point, say D seconds into the maneuver, he will possibly change the nature of his control to initiate precision tracking and reduce steady-state errors. By repeatedly flying this maneuver, he will learn just how much he can force a quick initial response, without producing overshoot and oscillation. The performance of this step target tracking task can be measured by rms tracking error and time-on-target for a given pipper size and total tracking time.

The pilot model is set up to perform this tracking task in just the way the pilot does it as described above. This is shown in Fig. 2. There will be two forms for the pilot compensation elevator command δ_e – one which provides the initial target acquisition; and the other, after time D has passed, which controls final precision tracking and eliminates steady-state errors. These are of the form:

Acquisition

$$\text{time} < D,\ \delta e_I = (\text{delay}\ \tau)\{K_{p_I}[\theta_e(t) + T_{L_I}\dot{\theta}_e(t)]\} \tag{1}$$

Tracking

$$\text{time} \geq D,\ \delta e_F = (\text{delay}\ \tau)\left\{K_{p_F}\left[\theta_e(t) + T_{L_F}\dot{\theta}_e(t) + K_{IC}\int_0^t \theta_e(t)\,\mathrm{d}t\right]\right\} \tag{2}$$

where θ_e is pitch angle tracking error.

In this way, the model is provided with error and error rate feedback terms for both phases of control, and is allowed to use integral control to reduce steady-state errors during final precision tracking. Much data on human transport time delays indicate that for the use of fixed form models, such as the one described here, a value of 0.3 s is the best representation of an asymptotically-trained, motivated pilot. This leaves the following quantities to be adjusted in order to perform a simulation of this step tracking task for the evaluation of a given aircraft configuration: K_{P_I}, T_{L_I}, D, K_{P_F}, T_{L_F}, K_{IC}.

This adjustment will be performed using the principle that the human pilot is able to optimize his control with respect to performance measures through learning during training exercises. For the analysis of step target tracking, it will be assumed that the pilot optimizes time-on-target, and that this leads to the best compromise of rapid target acquisition and steadiness of target tracking. The adjustment rule for the pilot model is: Choose the parameters any way that leads to a maximum time-on-target. In practice, it is easiest to use the following procedure:

1) Assume a pipper size and a total tracking time, T_F.

2) Set $D = T_F$. Increase K_{P_I} and T_{L_I} as required to obtain the most rapid acquisiton of target with moderate overshoot and oscillation.

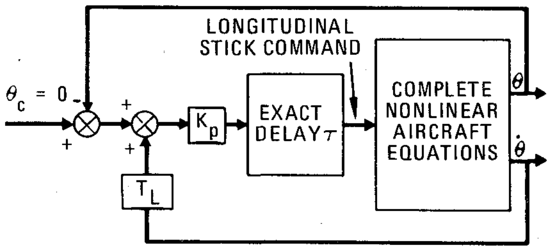

Fig. 1 Pilot-aircraft system model for pitch angle stabilization in turbulence.

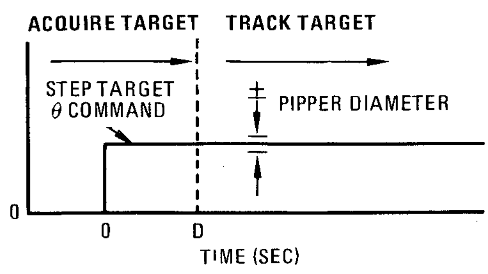

Fig. 2 Definition of step target tracking task.

3) With K_{P_I} and T_{L_I} fixed, set D to that time where θ is approximately 80% of the step command.

4) Vary K_{P_F} and T_{L_F} to increase time-on-target.

Steps 1-4 have resulted in an initial guess for the parameters. Final optimization requires use of a gradient method that obtains the partial derivatives of time-on-target with respect to all model parameters including time D. Once the model is adjusted, a matter that is easy in practice, rms tracking error and time-on-target can be obtained. Data for the Neal and Smith aircraft configurations were calculated in this manner and will be presented next.

Equations for the Neal and Smith configurations were programmed as described in their report, with the exception of the second order control dynamics. Forty-two configurations, series 1-7, were calculated with the aid of a programmable desk calculator and plotter, and the reader who is interested in applying this method is encouraged to repeat the analysis of the Neal and Smith configurations. A pipper size of 0.005 rad and total tracking time of 5 s have been assumed.

Figure 3 shows the calculated step tracking response of one of the better configurations surveyed, 6C, which was given a rating of $PR = 2.5$. In this case, the rapid acquisition of the target leads to low rms θ_e, while the steadiness of the precision tracking results in large time-on-target. On the other hand, Fig. 4 shows a poor configuration, 1F ($PR = 8$), that has sluggish response indicated by high rms θ_e. Even worse is the inability of this configuration to settle out on the target, so that time-on-target is mostly achieved during target crossings. Other configurations show a wide range of specific handling qualities problems: aircraft that exhibit great overshoot and others whose steady-state error is difficult to overcome, even with the use of the integral control compensation.

The primary objective of the flying qualities specifications, called out in MIL-F-8785B, is to establish numerical criteria that define levels of performance in terms of pilot ratings: Level I – PR 1-3.5, Level II – PR 3.5-6.5, and Level III – PR 6.5-9.5.

It is useful to examine the correlations of the rms θ_e and time-on-target data calculated for the Neal and Smith configurations with pilot ratings. The rms θ_e data are presented in Fig. 5. The expected result of increasing pilot rating number with increasing rms θ_e is clearly shown. However, if an attempt is made to draw a specification boundary as a vertical line at some rms θ_e value, in order to specify the performance in Level I or II, the result is that no lines can be drawn that do not also include many points from the wrong levels. This failure of rms θ_e to correlate with pilot ratings sufficiently well for specification purposes has been frequently noted, and attempts to weight other quantities along with it to produce stronger correlations were mentioned earlier. From the description of the piloted task, it is clear that the rms θ_e statistic is incidental, time-on-target being the primary performance measure. If calculated time-on-target is plotted against pilot ratings, there is again a strong correlation, as shown in Fig. 6. Unfortunately, this correlation is even less able to furnish specification boundaries than the rms θ_e vs pilot rating data.

From the preceding, it is clear that the single performance parameters rms θ_e and time-on-target are not sufficient to specify acceptable performance of the Neal and Smith configurations. If one considers that the pilot might trade off rms θ_e and time-on-target against one another in generating his

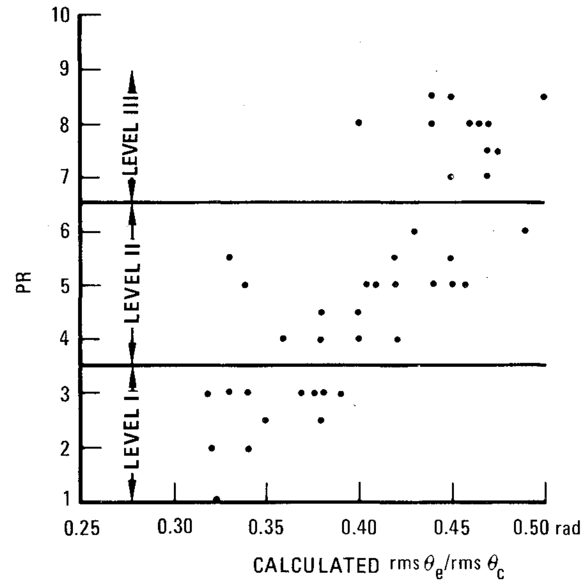

Fig. 5 Correlation of calculated rms θ_e with pilot ratings.

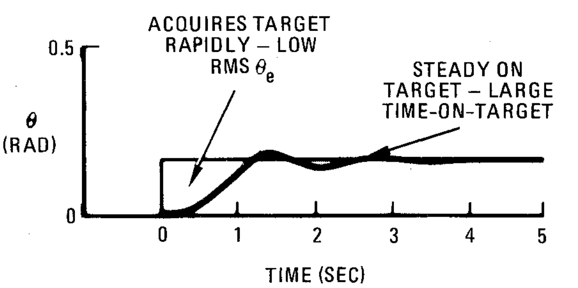

Fig. 3 Calculated tracking response of aircraft 6C($PR = 2.5$).

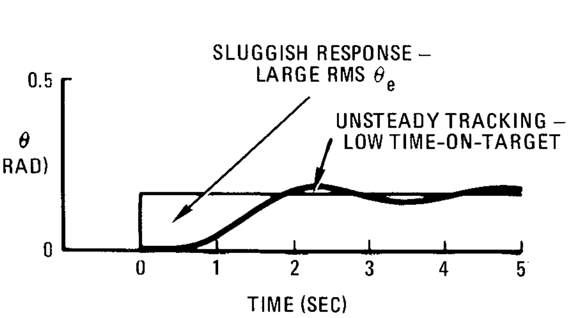

Fig. 4 Calculated tracking response of aircraft 1F ($PR = 8$).

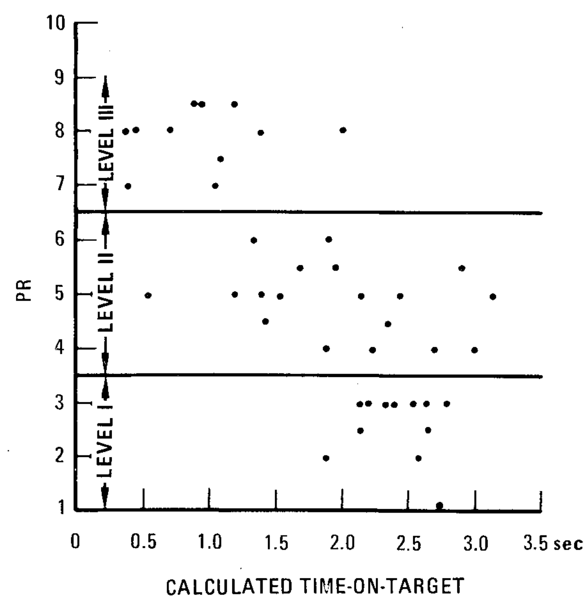

Fig. 6 Correlation of calculated time-on-target with pilot ratings.

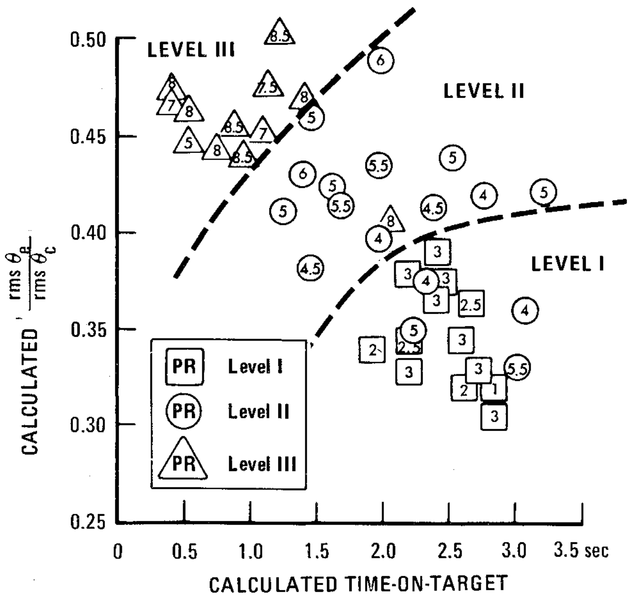

Fig. 7 Pilot ratings as functions of calculated rms θ_e and time-on-target.

pilot rating, these statistics become more useful. In order to see how this tradeoff may take place, rms θ_e is plotted vs time-on-target, with the point indicated by the minimum pilot rating given by a test pilot during the in-flight simulation. This is shown in Fig. 7, along with apparent boundaries that neatly separate the regions of Levels I, II, and III. With the exception of a few points that may have been unfairly rated owing to improper control sensitivity, all configurations lie in regions bounded by apparent curves that illustrate the tradeoff between the two performance measures. These curves show, for example, that a pilot will tolerate more sluggish response in a given level if the resulting time-on-target is especially good and conversely. Since the calculated parameters rms θ_e and time-on-target correlate with pilot ratings obtained during a flight test program that examined continuous tracking tasks, the representation of target tracking by the step target appears to be justified.

Final Remarks

Pilot ratings have been successfully correlated with regions in the two-dimensional space having calculated rms tracking error and time-on-target coordinates for the in-flight simulation data obtained by Neal and Smith. This shows the generality, versatility, and practicality of time domain pilot models. By demonstrating analytically the tradeoff between target acquisition and precise tracking for a short tracking period, the interrelationships of pilot ratings, the dynamics of pilot control compensation, and discrete maneuver flight test procedures are made clear. It is expected that future research into multiaxis step target tracking will yield similar correlations with flight test data. In the meantime, the time domain, urgency-decision pilot model can be readily used to evaluate a wide variety of continuous and discrete tasks encountered in the flying qualities of modern high performance aircraft.

Acknowledgment

This work was partially performed under Contract 33615-77-C-3008 for the U.S. Air Force Flight Dynamics Laboratory, FGC, Wright-Patterson AFB, Ohio.

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