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# PREDICTION, EVALUATION, AND SPECIFICATION OF FLYING QUALITIES BY MEANS OF STEP TARGET TRACKING

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## ABSTRACT

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 discrete manuevers. 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. Predicted step target tracking data for eighteen F-5E flight conditions are presented, and the use of the method for control system design is demonstrated using the YF-17.

## INTRODUCTION

Pilot ratings and pilot comments often refer to two basic kinds of evaluation:

1) How well can the aircraft be made to perform?
2) How hard is 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. Pilot rating prediction formulas have been developed that weight normalized statistical performance, usually an rms tracking error, along with an assumed correlate of pilot workload, such as the pilot lead compensation constant. Although these methods have 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. One basic problem with these approaches is that pilot model parameters of lead, reserve attention as defined by additional task

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requirements on the pilot, or other identifiable pilot characteristics are difficult to relate quantitatively 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.

Furthermore, 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, Reference 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.

References 2 and 3 present a simple and direct method for evaluating the performance of a tactical aircraft performing a discrete step target tracking maneuver. 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, Reference 4, was analyzed in terms of step target tracking.

The objective of this paper is to summarize References 2 and 3 and to present further details and applications of this flying qualities prediction and evaluation method by demonstrating YF-17 control system design improvement.

## DISCRETE AND STEADY-STATE TRACKING

Much analysis of closed loop piloted tracking has been published for random steady-state tracking tasks. These studies, References 5 and 6, for example, have demonstrated that pilot models are useful in the prediction of tracking performance of continuous random tracking tasks, and success has been achieved in correlating model parameters with pilot opinion ratings obtained from flight simulations, Reference 7.

However, in actual flight situations, the pilot is also faced with the task of performing quick corrections to flight path or attitude errors. The ability of an aircraft to respond well to such discrete corrections in a short tracking time is therefore of great importance to flying qualities analysis. This is particularly true in target tracking where the target must first be acquired and then precisely tracked.

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 the airplane 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 the overall task can be achieved for a given aircraft is the primary advantage of using time-domain pilot models to investigate step target tracking.

Consider a target that suddently appears above steady-state trim 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 then be measured by rms tracking error and time-on-target for a given pipper size and total tracking time.

The Northrop time-domain pilot model, Reference 3, is set up to perform this tracking task in just the way the pilot does it as described above. This is shown in Figure 1. There will be two forms for the pilot compensation elevator command $\delta_e$: 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

$$\text{time} < D, \quad \delta e_I = (\text{Delay } \tau)\left\{K_{p_I}\left(\theta_e(t) + T_{L_I}\dot{\theta}_e(t)\right)\right\}$$

TRACKING

$$\text{time} > D, \quad \delta e_F = (\text{Delay } \tau)\left\{K_{p_F}\left(\theta_e(t) + T_{L_F}\dot{\theta}_e(t) + K_{IC}\int_0^t \theta_e(s)\,ds\right)\right\}$$

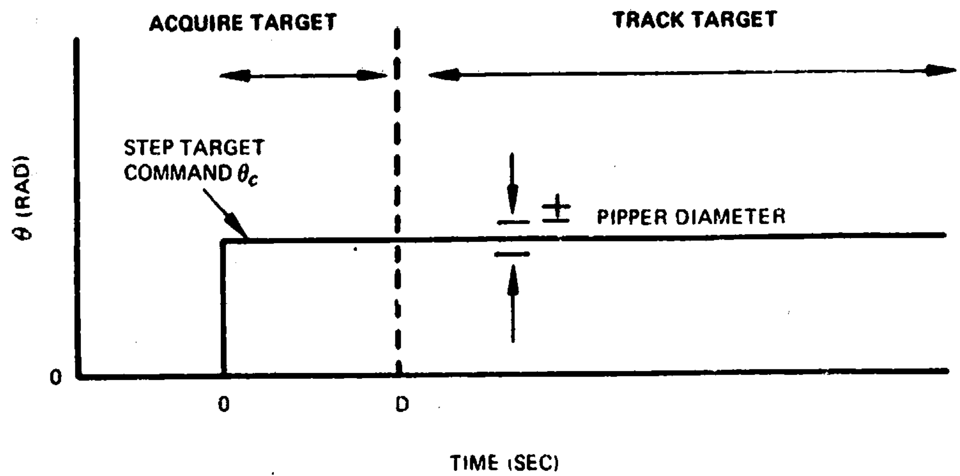



Figure 1. Definition of Step Target Tracking Task

where $\theta_e$ is pitch angle tracking error and the subscripts I and F refer to initial acquisition and final tracking, respectively. The $K_{IC}$ term represents a pilot's avoidance of steady state error by means of integral control. A pilot delay of $\tau = 0.3$ sec will be used.

The following quantities must be adjusted in order to perform a simulation of this step tracking task for the evaluation of a given aircraft configuration:

$$K_{P_I},\ T_{L_I},\ D,\ K_{P_F},\ T_{L_F},\ K_{IC}$$

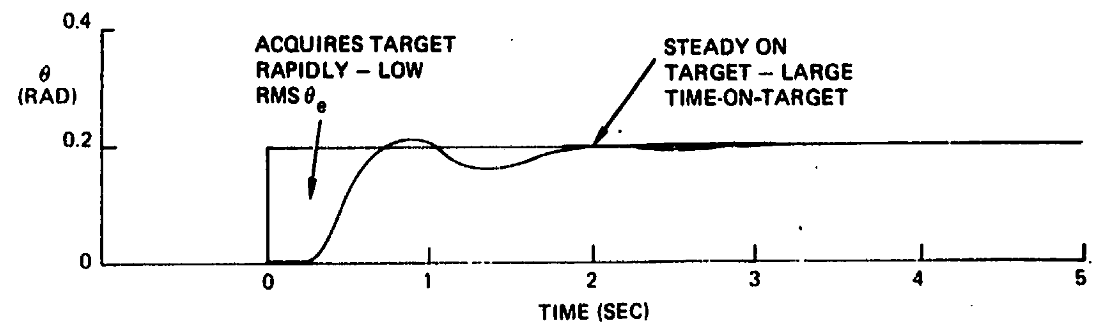
This adjustment is performed using an optimization principle. For the analysis of step target tracking, it will be assumed that the pilot optimizes time-on-target and that this leads to the best compromise of rapid target acquisition and steadiness of target tracking. The adjustment rule for the pilot model is thus: choose the parameters any way that leads to maximum time-on-target.

## PILOT — AIRCRAFT ANALYSIS OF LONGITUDINAL 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 1970. 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 commands. The reported pilot ratings and pilot comments cover stick forces, predictability of response, attitude control/tracking capability, normal acceleration control, effects of random disturbances, and IFR problems. Most pilot comments deal with initial response ("predictability of response") or precision attitude tracking control ("attitude control/tracking capability").

Forty-two configurations, Series 1 through 7, were calculated and presented in Reference 3. A pipper diameter of 0.005 radian, a step size of 0.2 radian, and a total tracking time of 5 seconds were adopted. Since the system was linear, any choice of step and pipper size that preserves the 40 to 1 ratio will lead to the same time-on-target and normalized rms $\theta_e$ statistics.

Figure 2 shows the calculated step tracking response of one of the better configurations surveyed, 7C, which was given a rating of PR = 1.5. In this case, the rapid acquisition of the target leads to low rms $\theta_e$, while the steadiness of the precision tracking results in large time-on-target. On the other hand, Figure 3 shows a poor configuration, 1F (PR = 8), that has sluggish response indicated by high rms $\theta_e$. 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

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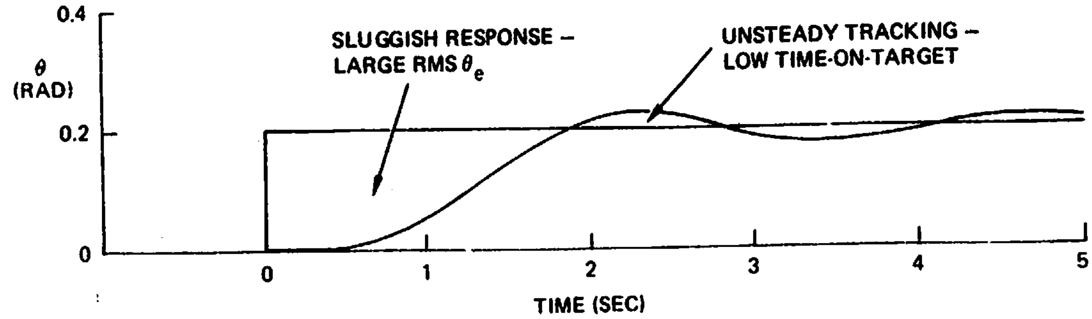
|---|---|---|---|---|---|---|---|---|
| $K_{PI}$ | - | 70.0 | $K_{PF}$ | = | 65.0 | TOT | = | 2.80 |
| $T_{LI}$ | - | -.05 | $T_{LF}$ | = | 0 | RMS$\theta_e$ | = | .32 |
| D | - | .5 | $K_{IC}$ | = | 0 | PR | = | 1.5 |

Figure 2. Configuration 7C Step Tracking Response




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $K_{PI}$ | = 4.6 | | $K_{PF}$ | = 7.0 | | TOT | = .4 |
| $T_{LI}$ | = .2 | | $T_{LF}$ | = .5 | | RMS$\theta_e$ | = .47 |
| D | = 1.5 | | $K_{IC}$ | = 0 | | PR | = 8.0 |

**Figure 3. Configuration 1F Step Tracking Response**

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 1 – PR 1-3.5, Level 2 – PR 3.5-6.5, and Level 3 – PR 6.5-9.5.

It is useful to examine the correlations of the rms $\theta_e$ and time-on-target data calculated for the Neal and Smith configurations with pilot ratings. The rms $\theta_e$ data are presented in Figure 4. The expected result of increasing pilot rating number with increasing rms $\theta_e$ is clearly shown. However, if an attempt is made to draw specification boundary as a vertical line at some rms $\theta_e$ value, in order to specify the performance in Level 1 or 2, the result is that no lines can be drawn that do not also include many points from the wrong levels. This failure of rms $\theta_e$ to correlate with pilot ratings sufficiently well for specification purposes has been frequently noted. From the description of the piloted task, it is clear that the rms $\theta_e$ 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 Figure 5. Unfortunately, this correlation is even less able to furnish specification boundaries than the rms $\theta_e$ vs pilot rating data.

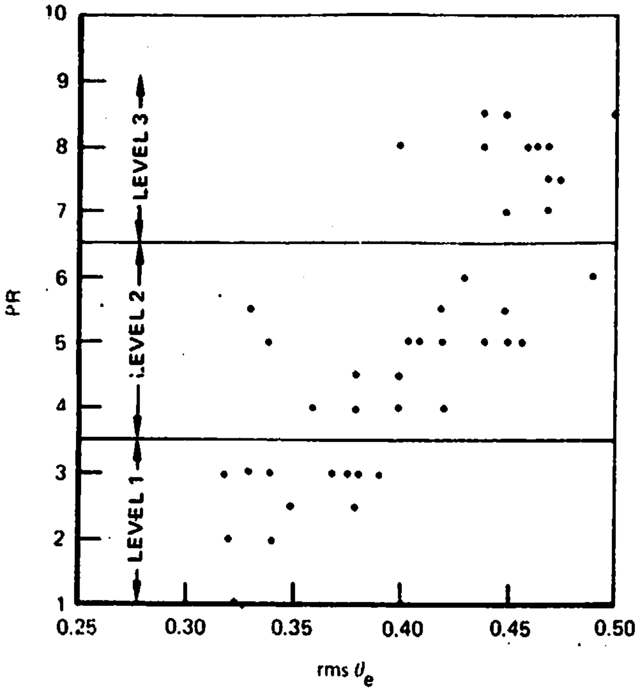



Figure 4. Correlation of rms $\theta_e$ with Pilot Ratings

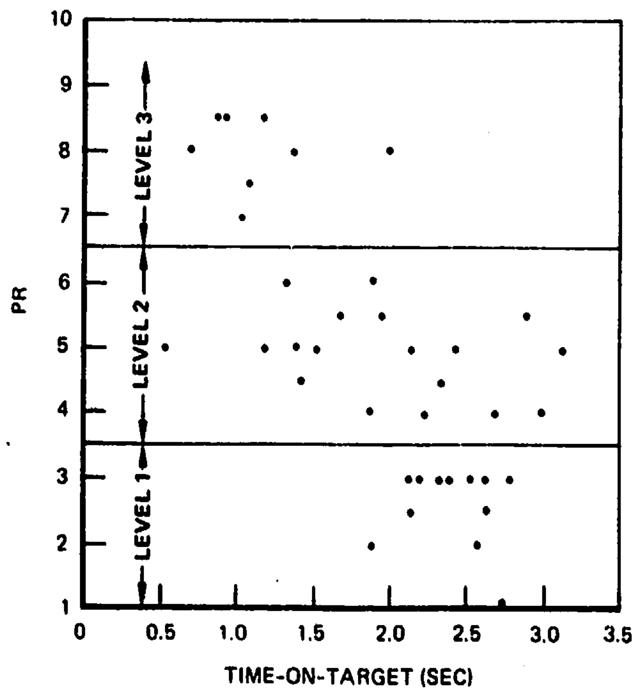



Figure 5. Correlation of Time-On-Target with Pilot Ratings

## CORRELATION OF STEP TARGET DATA WITH NEAL-SMITH PILOT RATINGS

From the above it is clear that the single performance parameters rms $\theta_e$ or time-on-target are not sufficient to specify acceptable performance of the Neal and Smith configurations. If one considers that the pilot might trade rms $\theta_e$ and time-on-target against one another in generating his pilot rating, these statistics become more useful. To see how this trade-off may take place, normalized rms $\theta_e$ is plotted versus 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 Figure 6 along with apparent boundaries that neatly separate the regions of Levels 1, 2, and 3. With the exception of seven points out of forty-two, all configurations lie in regions bounded by apparent curves that illustrate the trade-off between the two performance measures. These curves show, for example, that a pilot will tolerate more sluggish response in a given

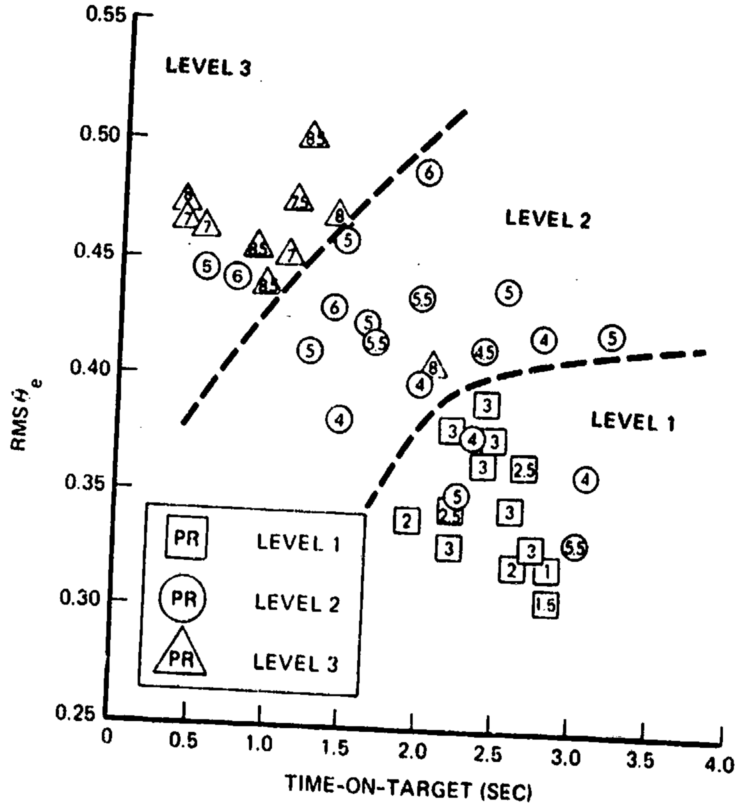



Figure 6. Pilot Ratings as Functions of rms $\theta_e$ and Time-On-Target

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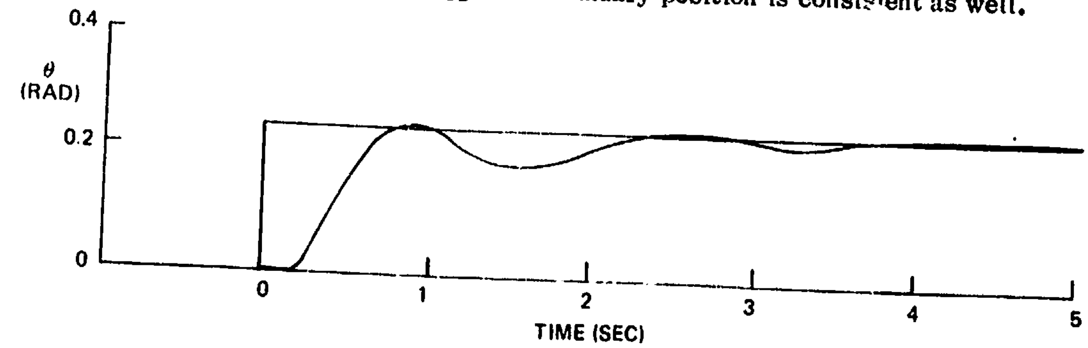
Level if the resulting time-on-target is especially good, and conversely. Since the parameters rms $\theta_e$ and time-on-target correlate with pilot ratings obtained during a flight test program that examined various tracking tasks, the representation of target tracking by the step target appears to be justified.

## VALIDATION OF THE STEP TARGET METHOD USING THE F-5E AIRCRAFT

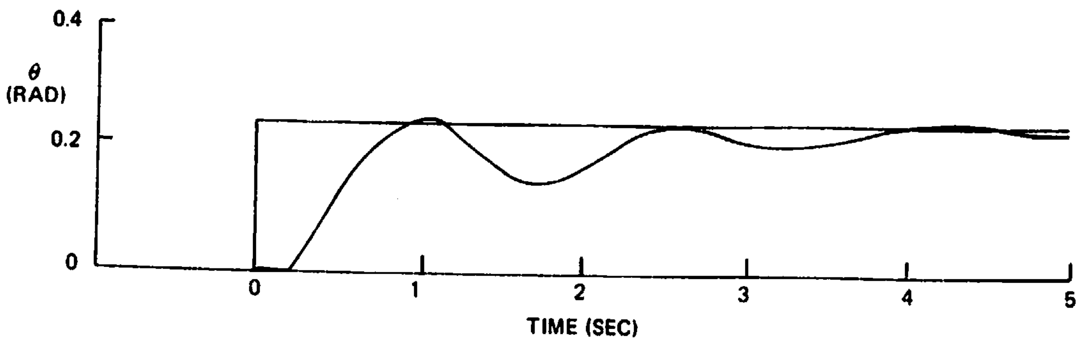
Further validation of the method was obtained by comparing F-5E aircraft with and without control augmentation at nine flight conditions representative of the primary maneuvering envelope. Full data is given in Reference 3 from which the examples shown in Figures 7 and 8 are drawn.

Comparison in Reference 3 of the step tracking responses for each flight condition with and without augmenter shows the importance of proper augmentation for good tracking response. In the augmented cases, the initial response is faster as reflected in the rms tracking error statistic, while the better damped dynamics lead to larger time-on-target values. To demonstrate the validity of the boundaries shown in Figure 6 based on the Neal-Smith data, the F-5E response data is plotted on these boundaries in Figure 9. Since the augmented F-5E has good Level 1 flying qualities, while the unaugmented aircraft may or may not meet Level 1 criteria, the Level 1-Level 2 boundary is consistent with the F-5E data. In this way, not only do the data of Figure 9 show the gradient direction of improving performance which characterized the Neal-Smith data, but the actual suggested boundary position is consistent as well.




| | | | | | |
|---|---|---|---|---|---|
| $K_{PI}$ | = -.49 | $K_{PF}$ | = -.6 | TOT | = 2.28 |
| $T_{LI}$ | = .3 | $T_{LF}$ | = .2 | RMS$\theta_e$ | = .31 |
| D | = .8 | $K_{IC}$ | = .06 | AUGMENTER | |

Figure 7. F-5E Case 4 Step Target Tracking Response

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|---|---|---|---|---|---|
| $K_{PI}$ | = - .23 | $K_{PF}$ | = - .3 | TOT | = 1.50 |
| $T_{LI}$ | = .5 | $T_{LF}$ | = .7 | RMS$\theta_e$ | = .34 |
| D | = .8 | $K_{IC}$ | = .09 | NO AUGMENTER | |

**Figure 8. F-5E Case 4 Step Target Tracking Response**

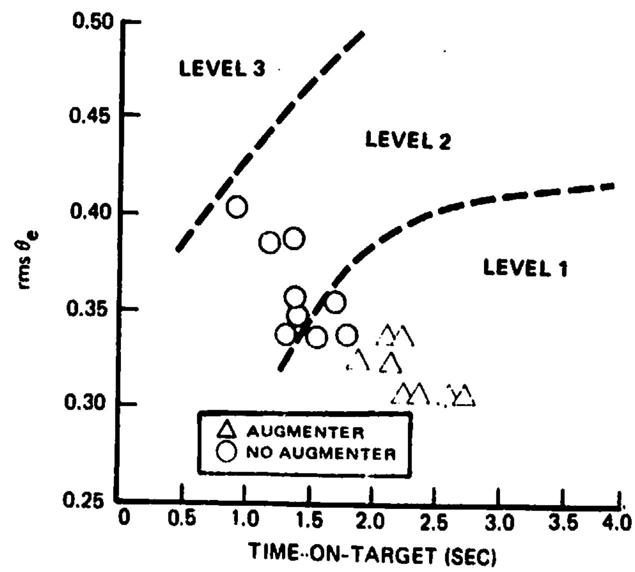


**Figure 9. F-5E Validation of Step Target Prediction Method**

## YF-17 CONTROL IMPROVEMENT DESIGN EXAMPLE

Recently, the step target method was used to evaluate and study possible control configuration improvement of the YF-17 aircraft. The baseline aircraft was designed to meet the Neal-Smith flight control criteria, but a multi-parameter perturbation of control constants has led to improvements in predicted tracking performance. Flight simulations are now planned to verify these predictions, which involved only small changes in control parameters.

The predicted improvements are shown for a number of flight conditions in Figure 10. Time-on-target and rms tracking error are plotted against the boundaries shown in Figures 6 and 9. The tail of each arrow represents the baseline YF-17 as flight tested, and the head shows the predicted response of the aircraft with the modified control design. It is clear that these small changes in the control parameters have produced substantial improvements in the predicted tracking performance. It should also be pointed out that these calculations were performed using the full nonlinear YF-17 aircraft and control descriptions.

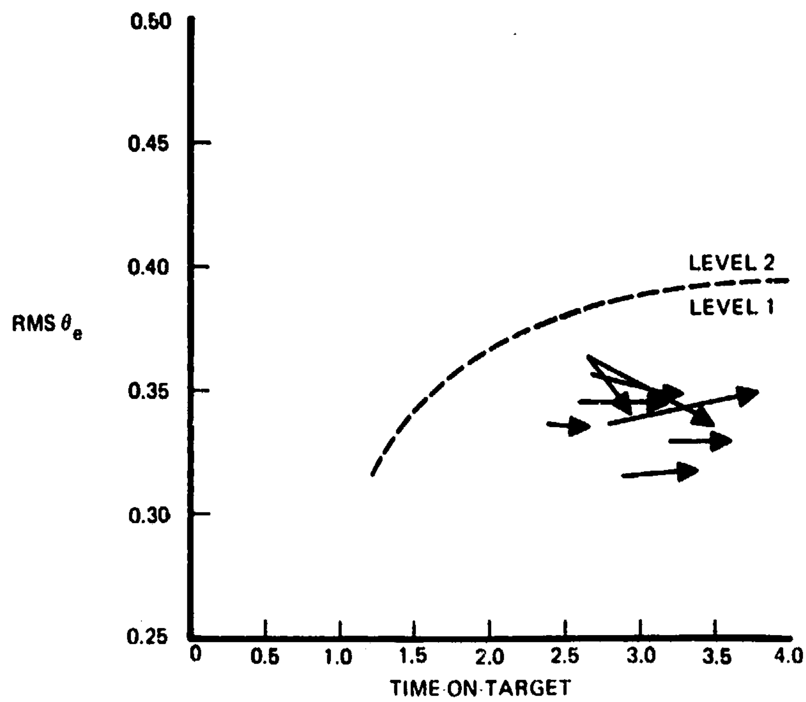


Figure 10. Predicted Improvement of Baseline YF-17 Step Target Tracking

The tracking improvements shown in Figure 10 were calculated using the same modified control parameters in each case. The most striking of the time-on-target improvements is seen by comparing the baseline step response shown in Figure 11 with the modified performance shown in Figure 12. The flight condition for this case is Mach 0.6 at sea level.

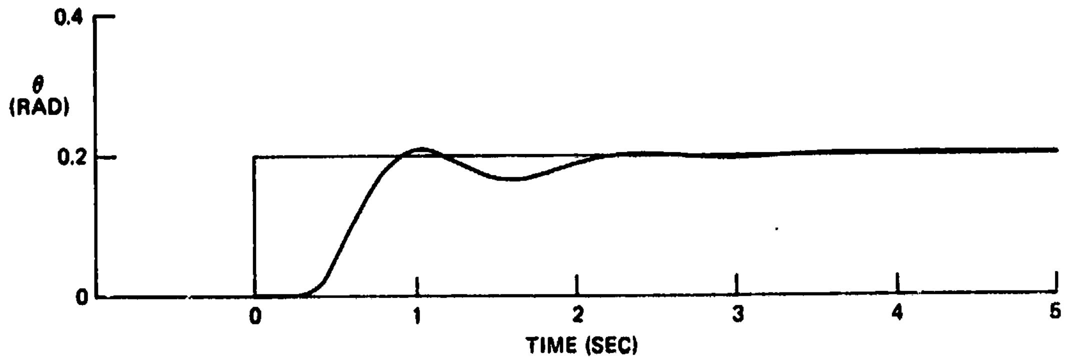


Figure 11. Step Target Tracking Response of Baseline YF-17

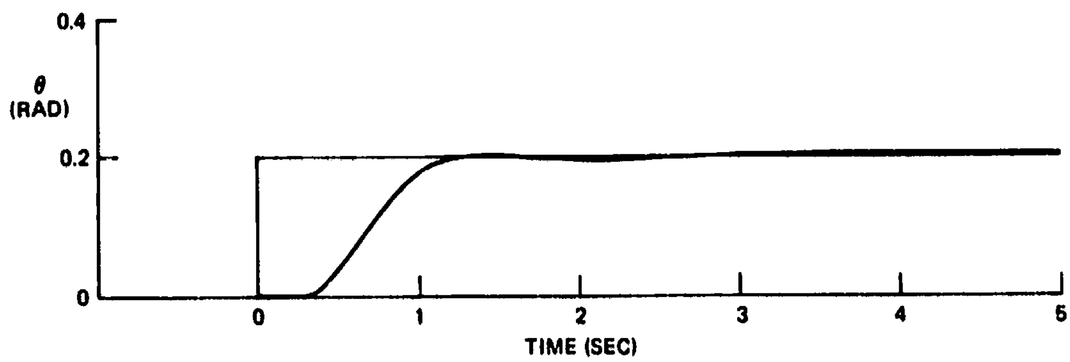


Figure 12. Step Target Tracking Response of Modified YF-17

SPECIFICATION OF AIR-TO-AIR TRACKING PERFORMANCE

The success of the step target tracking prediction method allows the following suggestions for tracking performance specification. For a specification to be a useful, discriminating, and fair criterion for tactical aircraft procurement, the following items must be satisfied:

1) The specification item must be numerical.

2) The specification item must correlate with pilot comments and pilot ratings.

3) The specification item must be easily measured in flight test or flight simulation.

4) The specification item must be reliably pre[illegible]ctable by analytical means for use in early design and development [illegible]ation.

5) The method that predicts the specification item must be applicable in a completely standardized form that evaluates the most general models of the candidate aircraft available.

6) The specification item must be valid for all current acceptable aircraft, and must exclude poor or unacceptable aircraft.

Unfortunately, these six requirements for military specification criteria have not all been met by any steady-state approach to the precision tracking problem. However, the transient method of step target tracking potentially satisfies these items. In particular, the step target method has the following characteristics that correspond to the requirements listed above:

1) The step target method is based on the numerical measures of rms tracking error and time-on-target as shown in Figure 6.

2) The two measures correspond with pilot comments in the following way:

| | |
|---|---|
| rms tracking error: | Quickness of response and overshoot characteristics |
| time-on-target: | Steadiness on target and precision tracking characteristics |

In addition, these two measures strongly correlate with pilot ratings obtained by Neal and Smith.

3) The use of step target tracking is already an established flight test procedure. It is completely standardized and easily tested.

4) The step target response is easily predicted for longitudinal step target tracking, and the extension to multiaxis target tracking is straightforward.

5) The method can be used with all representations of candidate aircraft from linear to full nonlinear equations.

6) The method clearly establishes performance boundaries for the Neal-Smith and F-5E aircraft. The only remaining requirement for MIL-F-8785B inclusion is further validation by current advanced tactical aircraft.

## 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. Validation by F-5E aircraft and a control improvement design study of the YF-17 further demonstrate the use and practicality of the method. 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 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

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