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MAXIMUM NORMALIZED ACCELERATION
AS A FLYING QUALITIES PARAMETER

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INTRODUCTION

In 1984, Maximum Normalized Rate (MNR) was presented as a Flying Qualities parameter [1]. Subsequent analysis of data from ground based simulation and flight test revealed the utility of a companion parameter, Maximum Normalized Acceleration (MNA). MNR and MNA profiles reveal the presence of both continuous and pulsed compensation strategies during discrete attitude tracking. In addition, MNR appears to be a suitable metric for pilot opinion in the LATHOS data base, while the MNR/MNA relationship is sensitive to pilot-induced-oscillation (PIO) and roll ratcheting problems.

Although the lateral roll mode of a conventional aircraft is perhaps the easiest dynamic mode to comprehend, there remain several poorly understood aspects of piloted control in this axis. For example, analytical prediction and fixed-base flight simulation tend to indicate that the shortest possible roll mode time constant is best. However, moving-base and in-flight simulations show clear disadvantages in such highly damped aircraft: pilot-induced-oscillations and roll-ratcheting often result during these cases [2]. Thus, real-world considerations, such as ride qualities effects on pilot compensation strategies, need to be accounted for.

Step Target Method

As part of an investigation of this problem, Northrop has developed an analysis technique known as the Step Target Method [3]. The Step Target method is essentially a one degree-of-freedom simulation, where an attitude command in the form of a step function is presented to a closed-loop pilot/aircraft model, as shown in Figure 1.

The aircraft dynamics model can be as simple or complex as the investigation warrants. Although discrete pilot modeling technology is largely still in development, an effective tracking model consisting of proportional blends of error and error rate are used as the basis of the Step Target method. An essential feature of this model is that it consists of two stages; the first stage contains values of gain and lead which are appropriate for gross target acquisition, while the second stage is tuned for fine tracking. The model automatically switches from the first stage to the second when the attitude tracking error is brought within 25% of the commanded attitude change.

PILOT MODEL FOR ACQUISITION:

$$\text{TIME} < \text{D}, \ \delta S_{P_I} - (\text{DELAY } \tau) \ \left\{ K_{P_I} (\theta_e(t) \ . \ T_{L_I} \dot{\theta}_e(t)) \right\}$$

PILOT MODEL FOR TRACKING:

$$\text{TIME} \geqslant \text{D}, \delta S_{PF} = \text{DELAY } \tau) \quad \left\{ K_{P_F} (\theta_e(t) + T_{L_F} \dot{\theta} e(t) + K_{IC} \int_o t \ \theta_e(s) \, ds) \right\}$$

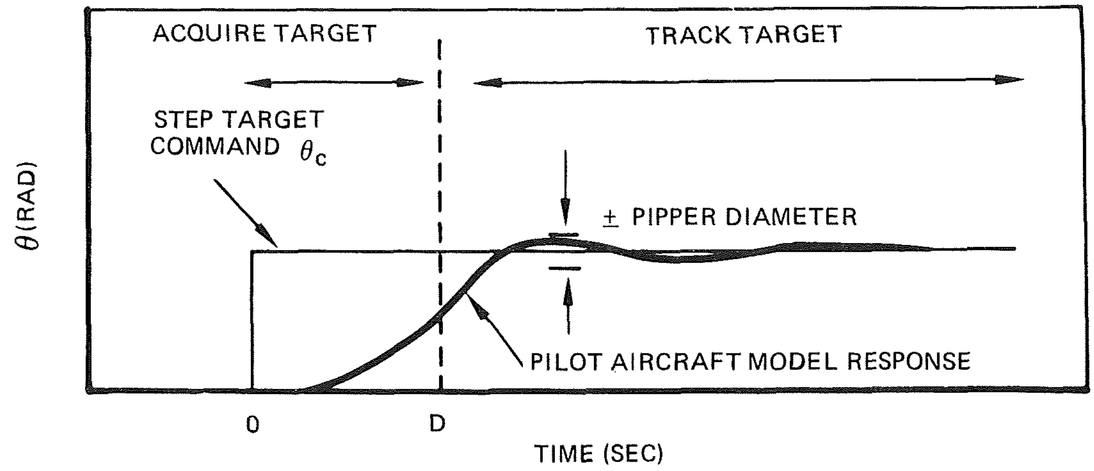

Figure 1. Definition of Step Target Tracking Task.

Previous Analysis of Neal-Smith Data

Onstott and Faulkner used the Step Target method to analyze an in-flight simulation performed by Neal and Smith [3]. The Neal-Smith simulation involved discrete pitch step attitude tracking, using the NT-33 variable stability aircraft [4].

The dynamic configurations modeled with the NT-33 were analyzed using the Step Target method. The two primary output parameters examined were Time-On-Target (TOT), and the Root-Mean-Square of the tracking error (RMS). RMS reflects the ability to maneuver the vehicle, while TOT, specified with respect to a tolerance of 2.5% of the commanded step magnitude, reflects freedom from overshoot and oscillation. Pilot model coefficients were adjusted to obtain maximum TOT for each individual vehicle configuration, which forces the quickest acquisition of the target, with low overshoot and oscillation. The resulting TOT and RMS values were compared to Pilot Opinion Ratings from the Neal-Smith experiment, and are shown in Figure 2 [5].

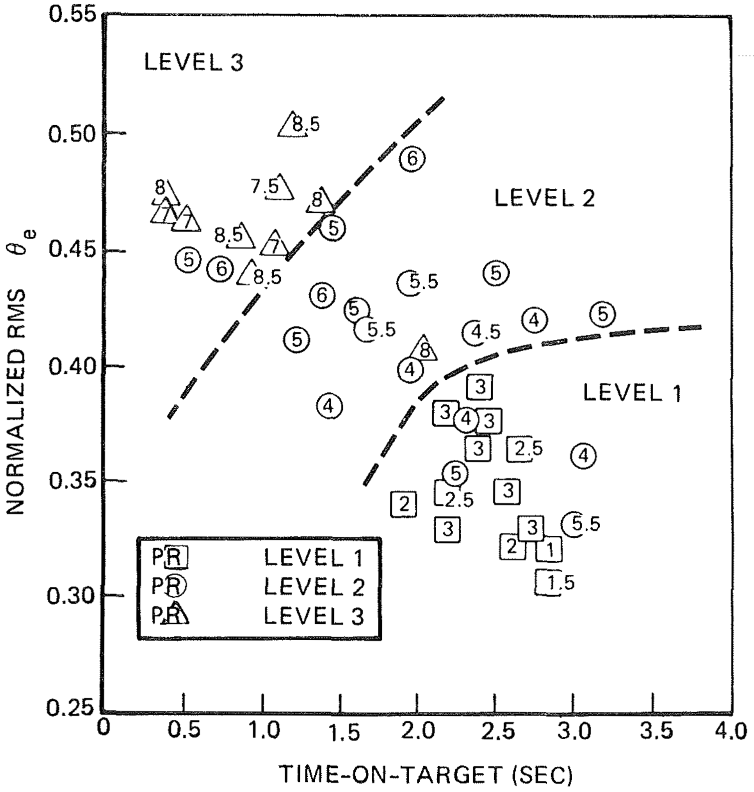

Figure 2. Pilot Opinion Ratings from the Neal-Smith Study as Functions of RMS and TOT.

Analysis of LATHOS Data

Further analysis with the Step Target method was conducted using additional in-flight simulation data from the NT-33. The Lateral Flying Qualities of Highly Augmented Fighters study (LATHOS) was used as a source of time histories and pilot comments [6].

Using a first order lag/delay aircraft model to simulate various LATHOS configurations, attempts were made to optimize the two-stage pilot model in the same manner used to generate the Neal-Smith correlations. Unlike the routine used in the Neal-Smith problem, the automatic optimizing algorithm proved to be badly behaved, resulting in very large values of gain and lead during a short first stage, followed by second stage coefficients which were stable but very small. In short, the model seemed to approximate, as well as it could, a time optimal pulsed solution. However, for the first order lag/delay aircraft models simulated in the LATHOS study, such an optimization problem for maximizing TOT is ill-posed in the absence of constraints imposed by higher order dynamics and nonlinearities; the model could be made to do arbitrarily well at the expense of sufficiently large control inputs.

As the two-stage model in its current state was shown to be ill behaved, analysis was performed using the single-stage model. Correlations between LATHOS pilot comments and the continuous pilot models were therefore sought. This effort yielded two conclusions:

1) Strong linear correlations were obtained between Pilot Opinion Ratings (POR), RMS, and TOT, as shown in Figure 3 [1]. This correlation is stronger than in Figure 2, which displays regional but not linear correlations.

2) For the LATHOS discrete task simulation, Pilot Opinion Rating is correlated well by a parameter called Maximum Normalized Rate (MNR), as shown in Figure 4 [1]. MNR is defined as the maximum roll rate achieved during the maneuver, normalized by the magnitude of the step command:

$$\text{MNR} = \max\ (d\phi / dt) \ / \ \phi\ \text{command}$$

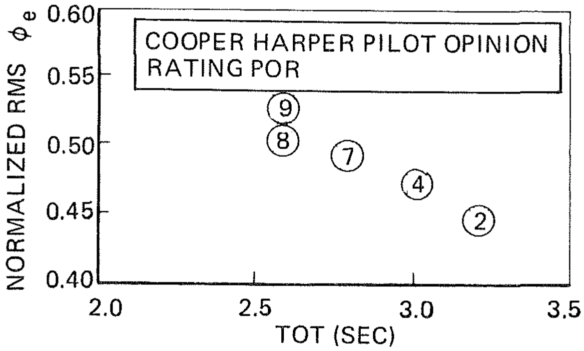

Figure 3. Pilot Opinion Rating, Correlated with TOT and RMS Bank Angle Response

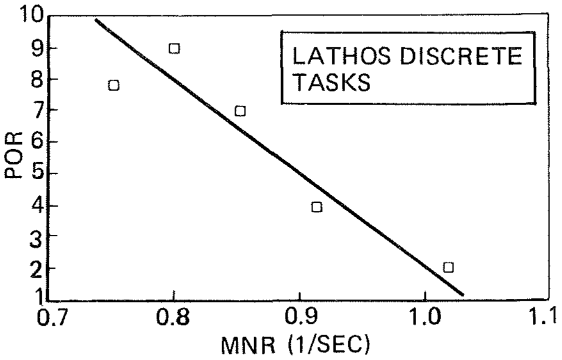

Figure 4. Relationship of POR to MNR

These results indicate that the LATHOS pilots were evaluating the configurations in terms that correlate with MNR derived from continuous constant control, even though time histories from [6] exhibit pulsed pilot control strategies. This left two questions to be resolved: 1) what control strategies were the NT-33 pilots using when they flew this discrete step problem in LATHOS, and 2) could simulator pilots achieve the extremely large TOT's that the model was indicating. In the case of the LATHOS simulations, pilots were given performance standards which did not require extremely large TOT. Nevertheless, the pilots often maneuvered very aggressively, as shown in published LATHOS time histories.

Northrop Ground Based Simulation

To investigate the mechanics of discrete maneuver attitude tracking, an investigative simulation study was performed on the Northrop Flight Controls Research Simulator (FCRS).

The FCRS consists of a generic single-place cockpit, representative of a single seat fighter aircraft. Out-the-window and instrument symbology display capabilities are provided by a Megatek 7000 video monitor. Computation was performed by a pair of Gould/SEL 32/55 minicomputers, configured to operate in parallel.

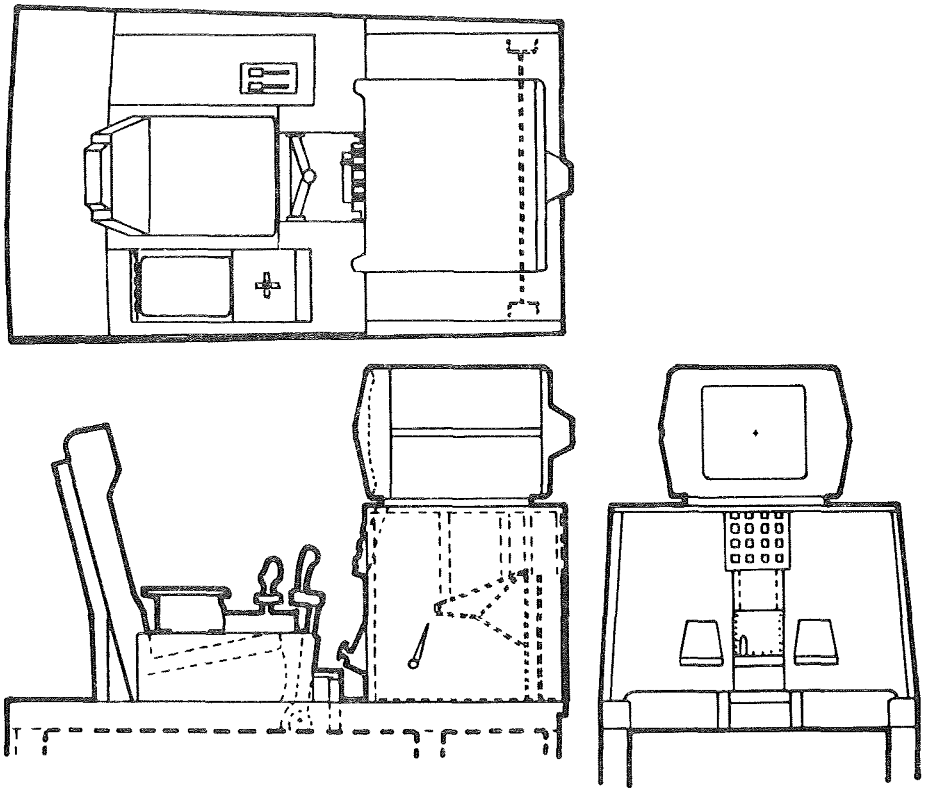

Figure 5. Northrop Flight Controls Research Simulator

A series of six discrete bank-angle attitude step-tracking commands was presented to the pilot during a 30 second trial. Commanded bank angles were randomly varied between 0.3 and 0.6 radians. After a brief pause, another set of six steps was presented. After ten sets, statistics were computed and printed. Data collected included RMS, TOT, MNR, and a new parameter, Maximum Normalized Acceleration (MNA). MNA is defined to be the maximum roll acceleration achieved during the maneuver, normalized by the magnitude of the step command:

$$\text{MNA} = \max\left(d^2\phi \; / \; dt^2 \right) / \; \phi \text{ command}$$

Simulator results exhibited abrupt pulsed pilot control. In fact, the pilots were utilizing full stick deflections during the tracking, producing large values of MNR, MNA, and TOT. Nevertheless, this type of aggressive control activity was identified in LATHOS time history data.

Comparison of LATHOS Data with Northrop Simulation Data

In order to allow a meaningful comparison of LATHOS time histories with the Northrop ground-based simulation data, a set of LATHOS cases was chosen using the following criteria:

1) The maneuver had to be flown with rapid acquisition of the commanded target value, with minimal overshoot and oscillation.

2) There could be no reported problems with control harmony, adverse force gradients, or other contaminating influences.

In comparing these selected cases against the ground based simulation data, similarities were observed: ground-based and in-flight simulation pilots both were able to push their TOT performance in a manner reminiscent of the automatic optimization algorithm. Data from both sources have been plotted together as functions of MNR versus MNA, as shown in Figures 6 and 7.

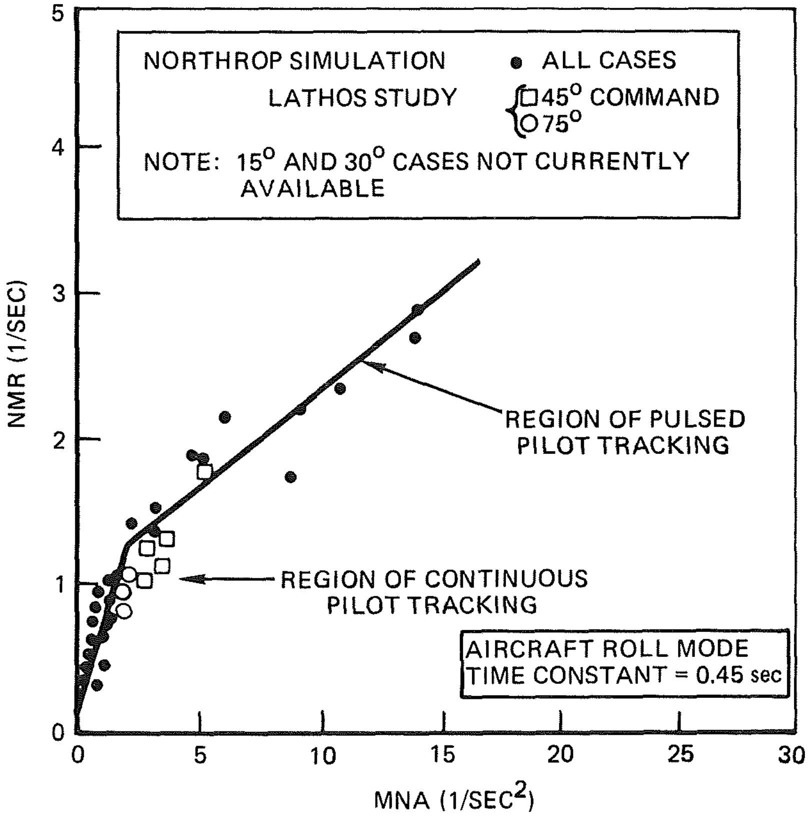

Figure 6. Correspondence Between LATHOS and Northrop Simulation Data for Roll Mode Time Constant of .45 seconds.

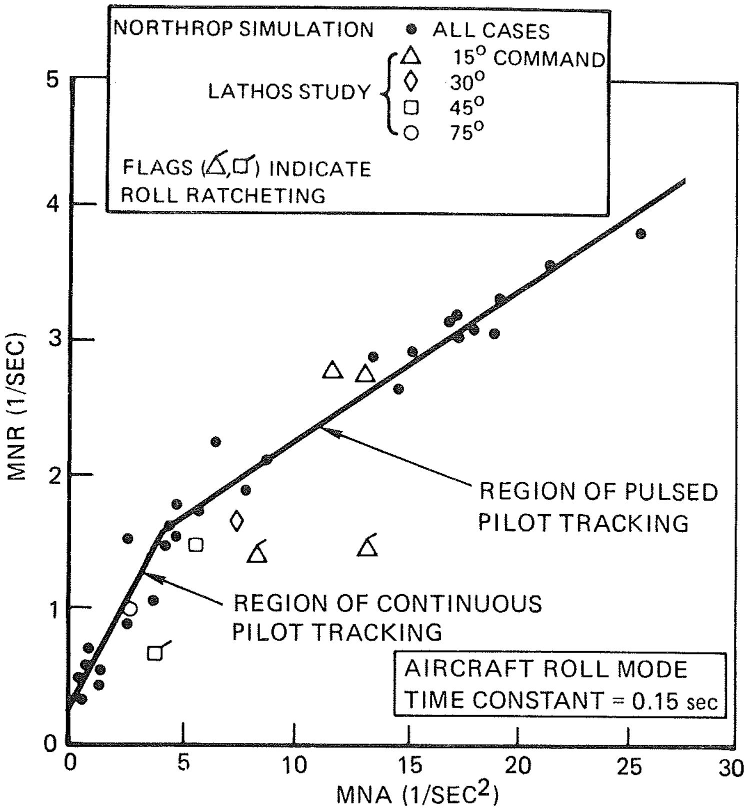

Figure 7. Correspondence Between LATHOS and Northrop Simulation Data for Roll Mode Time Constant of .15 seconds.

On these figures, the solid bent line approximates the Northrop flight simulation data. For each configuration, the step target method predicts where this abrupt change of slope occurs, in terms of MNR generated by the single stage model. For this reason, it appears that for lower MNR values, the pilot has adopted a continuous compensatory tracking strategy, while the higher MNR cases represent pulsed piloting techniques.

Figure 7 contains three points where LATHOS pilots experienced undesirable oscillations, called ratcheting. These points fall well to the right of the remainder of the data, indicating that, for this experiment, ratcheting is characterized by considerably higher values of MNA than the resulting MNR warrants.

Unfortunately, there are too few time histories currently available from the LATHOS study to allow validation of the above results. Even so, the following observations seem to be justified:

1) MNR versus MNA profiles indicate the presence of both continuous and pulsed control strategies.

2) MNR is a suitable metric for pilot opinion in the LATHOS data base, while the MNR/MNA relationship appears to be sensitive to PIO and roll racheting problems.

3) The relative distributions of MNR/MNA data for LATHOS step commands indicates that during in-flight roll maneuvering, pilots tend to limit lateral acceleration at the pilot station.

Comparison of Discrete and Continuous Tracking Tasks

Another simulation study was performed at Northrop, in order to compare continuous closed-loop tracking with step target tracking. The experiment, which was intended to refine the test matrix for an in-flight simulation involving the NASA Digital-Fly-By-Wire F-8, involved testing a number of lateral dynamics configurations, using both discrete and continuous tracking tasks [8,9].

Again, the FCRS simulator was utilized, and the step bank angle command task was used to provide a discrete compensatory task. The continuously varying bank angle command signal was formed from a sum-of-sines equation. The equation contained ten frequency terms, arranged to have an overall period of 50 seconds. In addition, the signs of the relative amplitudes were randomized for each run, in order to minimize pilot familiarity and task learning effects. The absoulute magnitude of the sum-of-sines equation was scaled to be plus/minus one radian. The frequency and amplitude characteristics used are shown in Figure 8.

INDEX	FREQUENCY $\left(\frac{RAD}{SEC}\right)$	RELATIVE AMPLITUDE
1	0.251	1.00
2	0.377	1.00
3	0.628	1.00
4	0.880	1.00
5	1.382	1.00
6	2.136	0.50
7	3.267	0.10
8	5.152	0.10
9	7.791	0.10
10	12.189	0.10

Figure 8. Frequency and Amplitude Data for the Continuous Tracking Task.

The experiment test matrix was composed of three pure time delays (0.100 , 0.175 , and 0.250 seconds) versus six roll mode time constants (TR) (0.2 , 0.3 , 0.4 , 0.6 , 0.8 , and 1.0 seconds).

Figure 9 shows the results of the CONTINUOUS tracking experiment. Points corresponding to each of the three values of delay are connected by straight lines. The apparent effect of delay is to displace the tracking data, for each roll mode time constant, toward greater values of tracking error normalized by the RMS of the tracking command. This figure also illustrates that an increased roll mode time constant will result in a decreased tracking capability. An exception to this trend occurs in the very highly damped case of TR = 0.2, where rate perception effects are encountered in the simulation.

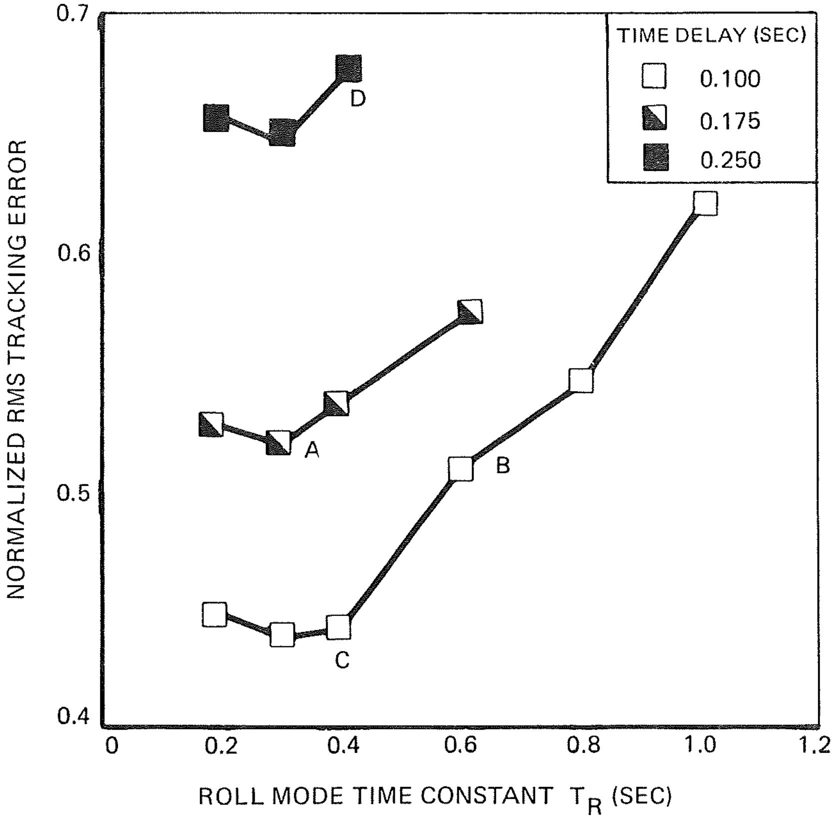

Figure 9. Summary of Continuous Tracking Averages, Showing Effects of Time Delay and Roll Mode Time Constant

The same test matrix was used in the DISCRETE tracking experiment. Figure 10 presents the profiles of MNR versus MNA produced by tracking the discrete Step commands. Clearly, there is a trend for higher values of MNR to be associated with higher values of MNA. The greater values of time delay lead tend to result in lower values of both MNR and MNA for a given value of TR.

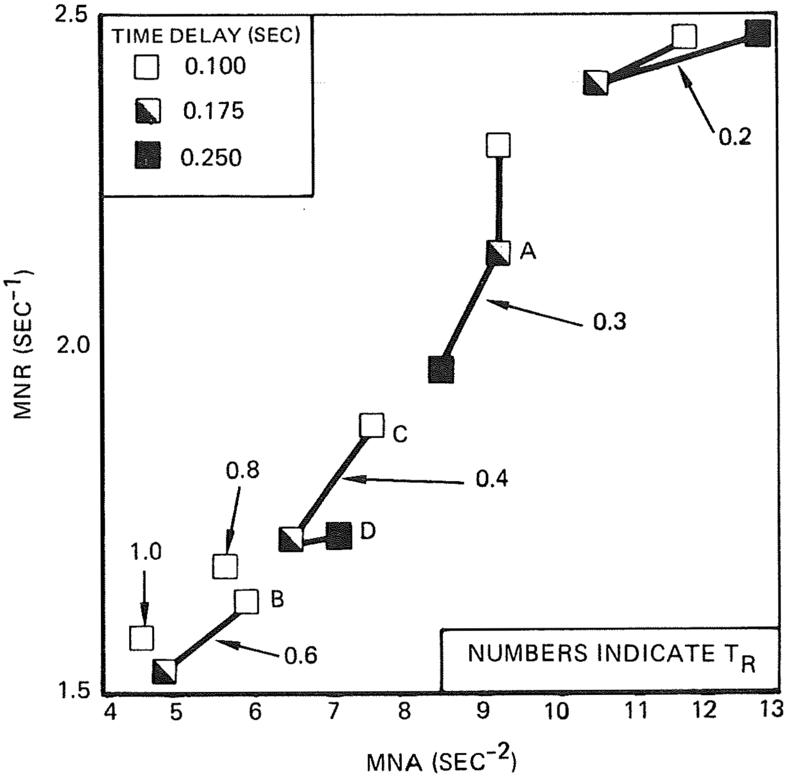

Figure 10. MNR vs. MNA for Discrete Tasks, Showing Effects of Time Delay and Roll Mode Time Constant.

Figures 9 and 10 both show smooth variations in plotted parameters, with respect to the corresponding aircraft dynamics. However, it should be noted that the associated sensitivities do not necessarily correspond. This can be observed through comparison of the two points labeled 'A' and 'B' on both figures. In Figure 9, these points are associated with roughly the same RMS tracking errors, while on Figure 10, 'A' and 'B' are greatly separated in both MNR and MNA parameters. Thus, as the previous experiment revealed a correlation between MNR and Pilot Opinion Ratings, one would have anticipated that 'A' and 'B' would receive quite different POR's, even though they exhibit nearly identical RMS tracking error scores in the continuous tracking task. Conversely, the points labeled 'C' and 'D' appear quite dissimilar in terms of RMS tracking error, as shown in Figure 9, while the same two points are close together in terms of MNR and MNA, as shown in Figure 10.

SUMMARY OF ANALYSIS

The two parameters MNR and MNA have been shown to be useful in Flying Qualities analysis. MNR was shown to correlate with Pilot Opinion Rating in the LATHOS data base, while MNA reflects PIO and roll ratcheting. Profiles of MNR versus MNA reveal the presence of pulsed compensation strategies in both ground based and in-flight simulation. Furthermore, comparison of continuous and discrete attitude tracking simulation data reveals that these two tracking tasks exhibit independent sensitivities to aircraft characteristics.

ACKNOWLEDGEMENT

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