AFFDL-TR-69-120

A NEW APPROACH TO THE SPECIFICATION AND EVALUATION OF FLYING QUALITIES

RONALD O. ANDERSON

TECHNICAL REPORT AFFDL-TR-69-120

JUNE 1970

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

71

A NEW APPROACH TO THE SPECIFICATION AND EVALUATION OF FLYING QUALITIES

RONALD O. ANDERSON

FOREWORD

This report details the results of an in-house study of an entirely new approach to flying qualities specification, with specific application to VTOL hover dynamics. The approach is based on a new pilot-vehicle analysis concept called the minimum pilot rating method. The latter has many other applications.

The work was performed under Project 8219, Task 821909, Work Unit 004, which documents the AFFDL participation in a current joint Air Force-Navy-Army development of a V/STOL Flying Qualities Specification. The basic material was prepared over the period of June-August 1969 and presented to the Joint Services Group in draft form as FDCC TM 69-2. The minimum pilot rating method has potential beyond VTOL specifications, however, so the same basic material is presented here in a more refined form, with suggested extensions and applications.

Several of the author's colleagues assisted in one way or the other in this program. Capt James Dillow performed all of the digital computer work that is only touched upon in this report. However, this digital computer program may be the key to wide-spread (in a piloting task sense) application of the "new" methods. Also, Paul Pietrzak and Robert Woodcock assisted in the analog computer operation. The latter provided much encouragement during all phases of the work. Finally, the authors of the many references cited in the text should be mentioned here, but the list is far too long. Nonetheless, their ideas, and careful data compilations, really made this project possible.

This technical report has been reviewed and is approved.

C.B. Westbrook

C. B. WESTBROOK
Chief, Control Criteria Branch
Flight Control Division
AF Flight Dynamics Laboratory

ABSTRACT

A study of the correlation of pilot model parameters and closed-loop performance with pilot opinion of VTOL hover dynamics was conducted. The encouraging results suggested a pilot-vehicle analysis method of predicting pilot model parameters, closed-loop pilot-vehicle performance with gust inputs, and pilot opinion ratings for a wide range of vehicle dynamics. This approach was, in turn, used to predict ratings for comparison with fixed base, moving base, and flight test results for VFR conditions. Again the results were promising, and a new method of specifying hover dynamics followed naturally. The new pilot-vehicle analysis concept, called the minimum pilot rating method, is discussed in terms of applications to other tasks, flying qualities specification, and control system design.

CONTENTS

FIGURES

TABLES

SYMBOLS

R	Pilot rating; calculated from rating expression, or predicted
R_1	Element of rating expression depending on performance
R_2	Element of rating expression depending on inner-loop pilot lead
R_3	Element of rating expression depending on outer-loop pilot lead
PR_H	Actual pilot rating for the precision hover task
T_N	Neuromuscular time constant
T_L	Pilot lead time constant
T_{L_θ}	Pilot lead time constant in pitch
T_{L_x}	Pilot lead time constant in longitudinal displacement
q (p)	Pitch (roll) rate
θ	Pitch angle
θ_x	Pilot's mental pitch command
x (y)	Longitudinal (lateral) displacement
σ_q (σ_p)	Standard deviation of pitch (roll) rate
σ_x (σ_y)	Standard deviation of longitudinal (lateral) displacement
$\sigma_{u_g}(\sigma_{v_g})$	Standard deviation of longitudinal (lateral) gust disturbance
σ	$\sigma_x+10\sigma_q$ or $\sigma_y+10\sigma_p$; σ_m=Required performance=constant
ω_b	Break frequency of gust input spectrum
$\Phi_{u_g u_g}(\omega)$	Gust input power spectral density
τ_θ	Pilot reaction time delay in pitch loop
τ_x	Pilot reaction time delay in displacement loop

τ	$\tau_\theta + T_N$
τ_c	First order actuator time constant
δ'	Control stick deflection without τ effects
δ	Control stick deflection
T'_{L_x}	$T_{L_x} K_{p_x}$
T'_{L_θ}	$T_{L_\theta} K_{p_\theta}$
ω_{c_θ}	Approximate closed-loop crossover frequency in pitch
ω_{c_x}	Approximate closed-loop crossover frequency in translation
u	Velocity in x-direction
X	Force in x-direction divided by aircraft mass
X_u	$\partial X/\partial u$
X_δ	$\partial X/\partial \delta$
g	Acceleration due to gravity
M	Pitching moment divided by pitching moment of inertia
M_q	$\partial M/\partial q$
M_δ	$\partial M/\partial \delta$
M_u	$\partial M/\partial u$
M_θ	$\partial M/\partial \theta$
k	General coefficient in rating terms
K_{p_θ}	Pilot gain in pitch
K_{p_x}	Pilot gain in displacement
Y_{p_θ}	Pilot describing function in pitch loop
Y_{p_x}	Pilot describing function in displacement loop

MATHEMATICAL SYMBOLS

$\doteq$	Approximately equal to
$<$	Less than
$\leq$	Less than or equal to
$>$	Greater than
∂	Partial differential
$\lvert\overline{\ }\rvert$	Average value of absolute magnitude
$\frac{d}{dt} = (\dot{\ })$	Denotes derivative with respect to time
$(\overline{\ })$	Denotes angular measurement in degrees
s	Laplace operator
e	2.7183
Δ	Increment
rms	Root Mean Square

SECTION I

INTRODUCTION

With an ever increasing reliance on flight control augmentation to provide acceptable flying qualities for high performance, multi-purpose design military aircraft, two problems arise in respect to the specification of flying qualities; namely,

a. To treat the specification problem as an extrapolation of past experience, a whole array of possible types of augmentation must be considered, with attendant requirements for each (this approach was initially considered for a new V/STOL Specification, Reference 1). Not only are data (e.g. attitude systems, and rate systems for the VTOL hover task) difficult to amass, but the lack of an underlying set of "true" requirements also becomes apparent. That is, one should certainly state what is really required, and this should apply to any and all means of obtaining these "basic" requirements.

b. On the other hand, the current conventional vehicle specifications are based on the a priori assumption that the aircraft flies "like an airplane". If the vehicle dynamics are indeed augmented, the resulting "effective" vehicle dynamics could easily present seven or more aperiodic modes in place of the conventional longitudinal pair of oscillatory modes. The former may even yield better pilot acceptance, but the question remains, "Does the effective system meet the flying qualities specification?"

Although both of the above problems have become increasingly more acute over the past few years, the "normally augmented" VTOL hover task has brought things to a head. In short, some new approach must be evolved.

As part of a joint AF-Navy-Army effort to draft a V/STOL flying qualities specification, a new approach to hover flying qualities specification was evolved and tested. This evolution is discussed in the remainder of this report, along with a new pilot-vehicle analysis method that has implications far beyond the specification of VTOL hover dynamics. The report organization is outlined in the following paragraphs.

Section II presents a correlation of measured pilot model parameters, closed-loop performance, and pilot rating for VTOL hover from a single data source. This correlation leads to a mathematical method of calculating pilot opinion rating given pilot parameters and pilot-vehicle performance measures. In a sense this "curve fit" could be used as the basis for a new form of flying qualities specification in itself.

In order to test rating calculations against other hover data, where measured pilot parameter data and closed-loop performance are not specified, a procedure to predict these parameters was needed. Such a procedure is presented in Section III. The single, most critical, new assumption made is that the pilot attempts to minimize his numerical rating (large values represent poor ratings) of the dynamics in question; a "reasonable" but unproven idea. This section should be of particular interest to manual control theory readers.

Next, Section IV presents a correlation of minimum pilot rating analysis predictions, for the hover task, with data from some seven different sources other than that used in the original "curve-fit" of Section II. These correlations provide the "proof" of the method, and should be of particular interest to flying quality oriented readers.

Finally, Section V discusses the application of the minimum rating method to other tasks, to the detailed specification of hover dynamics, and to aircraft control system design in general. Each of these applications suggests further work, and very interesting future possibilities.

Section VI contains a brief overall summary of the work to date, and specific conclusions.

SECTION II

PILOT RATING AS A FUNCTION OF PILOT MODEL PARAMETERS AND CLOSED-LOOP PERFORMANCE

The concept of mathematical models of the human operator, or pilot, has developed over the years to play a prominent role in modern manual control theory. Furthermore, the suggestion that pilot model parameters are, in turn, related to pilot opinion rating is not new (Reference 6). For the hover task, Reference 5 discusses the relation in general, while References 2 and 4 indicate specific trends. It remains, however, to consolidate these ideas into a complete correlation, and Reference 7 provides further data for this purpose.

It has been generally observed (Reference 7) that pilot opinion rating is directly related to pilot lead generation (T_L) with the trend of an increased numerical rating (less desirable) with increase in lead. Also, a trend of increased rating with an increase in closed-loop mean absolute error is evident in Reference 7. Although the piloting tasks considered in Reference 7 did not include VTOL hover under gusty conditions, the pilot rating data in References 2 and 4 show similar trends. Also, the latter references include measured pilot model parameters for an assumed pilot form that produced a good fit to measured values of closed-loop pilot-vehicle performance.

Assuming that lead generation and closed-loop performance are the main factors (there are certainly many others) that affect pilot rating of longitudinal dynamics in hover under the influence of random gust inputs, the data in Reference 2 were used to develop the following expression for pilot rating as a function of the above factors:

$$R = R_1 + R_2 + R_3 + 1.0$$

where: $R_1 = \frac{\sigma - \sigma_m}{\sigma_m}$, $\sigma_m = 0.80$ = required performance

$\sigma = \sigma_x + 10\sigma_q$

$$0 \leq R_1 \leq 2.50$$

and σ_x = standard deviation of x displacement in feet

σ_q = standard deviation of pitch rate in rad/sec.

also, $R_2 = 2.5\, T_{L_\theta}$

$R_2 \leq 3.25$ T_{L_θ} = Pilot lead time constant in pitch (seconds) and $R_3 = 1.0\ T_{L_x}$

$R_3 \leq 1.20$

T_{L_x} = Pilot lead time constant in displacement (seconds)

Pilot ratings, PR_H, for the cases where measured pilot parameters exist, are shown in Figure 1 vs. the rating calculated with the above expression for the data in Reference 2. These results are also summarized in Table I as cases PH1 to PH36.

Although the rating expression was obtained as an "eyeball fit" to the data (instead of using a more elegant linear regression analysis) the results in Figure 1 show a correlation within one-half rating unit in most cases. In three cases (PH22, PH32, PH34) the correlation difference is greater than one rating unit, but:

a. one pilot rated a configuration within 0.12 rating units of R, while the other pilot rating, indicated by a line connecting the two points, differed from R by more than one unit (PH22).

b. in two cases large gust intensities, indicated in the figure by the value of σ_{u_g} next to the point, seemed to affect the fit (PH32 and PH34).

In any event, most of the data correlates with the rating expression within less than one rating unit, which is within the accuracy of most flying quality analyses. It should also be noted that a rating range of about 2.0 to 6.5 is included (Figure 1), and various types of "systems" ($M_q \ll 0$ is a rate system, $M_\Theta \ll 0$ is an attitude system) are represented (Table I). Finally, note that the reason for the rating is apparent in Table I. For example, PH5 is rated poor because of performance (large R_1), while PH26 is rated poor because of the need for excessive pitch lead (large R_2).

Three of the above cases are re-examined under moving and fixed base conditions, and reported in Reference 4. The rating expression yielded values as follows based upon measured pilot parameters and performance (see Table II also):

Case		Pilot Rating	Calculated Rating
PH10	NM	5.0	6.4
	NF	7.0	5.3
	U	4.25	3.9
PH11	NM	4.0	4.6
	NF	5.5	5.2
	U	3.0	2.8

Case	Pilot Rating	Calculated Rating
PH12 NM	3.0	4.9
NF	5.0	4.7
U	3.25	2.6

NM = Northrop Moving; NF = Northrop Fixed; U = United Fixed

The calculated ratings for the moving base (NM) are larger than the pilot ratings in all cases. The best overall correlation is seen in Case PH11 where even though different simulations of the *same configuration* produced different ratings, the calculations follow the true ratings very well. No explanation for the differences in calculations and the Case 10 NM and Case 12 NM data is offered at this point, except that pilot rating scatter is very evident in much of these moving base data.

Based upon the earlier discussion in this Section it would be nice to state that "pure theory" yielded the R expression. It was, however, a simple "curve fit" to the data. Only the form (e.g., R_1 reflects performance, R_2 and R_3 reflect pilot "work load") was "theoretical," as indicated above. The idea of increased rating with increased lead generation (R_2 and R_3) is not new for this task, and others (Reference 5). However, numerical values are difficult to come by. The second form, R_1, is also not new since various performance measures have been used in attempted correlation with pilot rating, "work load," etc. In fact, Reference 3 presents one such measure. Perhaps what is new here, at least to the author, is that both performance *and* pilot leads are used *quantitatively*. However, other analyses (Reference 6) *may* have used some indirect measure of performance.* At any rate, each term is discussed below, for the most part, in hind-sight:

R_1: $2.5 \geq R_1 = \frac{\sigma - \sigma_m}{\sigma_m} \geq 0$. This expression is an attempt to incorporate several "logical" factors. First, some minimum performance, σ_m, is necessary to do a given task. If the actual closed-loop performance is equal to, or smaller than, σ_m, no increase in pilot rating is indicated. Stated another way, in a disturbance environment (u_g in this case), $\sigma = 0$ is not "expected". Therefore, the normalized form shown was selected. The value of σ_m, for the hover task, was taken as the lowest value of $\sigma = \sigma_x + 10\sigma_q$ encountered in the data in Table I. It was equal to about 0.70 for one pilot, and 0.90 for the second, so an average of $\sigma_m = 0.80$ was used. The form of σ itself was simply in keeping with the data. The σ_x part is obvious, since the task is to keep $x = 0$. However, very large excursions in q would represent excessive attitude changes occurring during the process of keeping x small, so the $10\ \sigma_q$ was added as an inner-loop performance measure. The factor 10 just seemed to fit the data and produces rating increments that are twice as large for σ_x as for σ_q with a "fair" configuration.

---

* Reference 22, received after this report was drafted, presents rating correlations with closed-loop time constants. Gust effects are not considered.

The unity coefficient of the normalized performance term R_1 does correspond with other data. Figure 27, Reference 7, shows pilot rating vs. mean absolute error, with only the input variance changed (e.g., controlled element fixed). Using $\overline{|e|}$ as an approximation to σ, the k/s data in this figure show

$$R_1 = k\left(\frac{\sigma - \sigma_m}{\sigma_m}\right) \quad \text{or} \quad 2.5 \doteq k\left(\frac{1.25 - .4}{.4}\right)$$

so k = 1.18 if the $\overline{|e|} = .4$ is taken as the normalization value.

This indicates the "curve-fit" coefficient of R_1 is, at least, reasonable in comparison with other data. The slope $\Delta R/\Delta \overline{|e|}$ does not correspond very well with $\Delta R_1/\Delta\sigma$, however, so some form of normalization appears necessary for general applicability.

The upper limit on R_1 such that $R_1 \leq 2.50$ is empirical. It fits the hovering data, in particular, cases PH 18 - 22 (Reference 2). Two possible, but weak, arguments for this upper limit follow:

a) If no pilot leads are required, then the maximum R determined by performance alone becomes R = 3.5 (Figure 27, Reference 7, shows no apparent limit, however). This happens to be the acceptable-unacceptable boundary and, perhaps, beyond this "who cares".

b) If each of the limiting values of R_1, R_2, and R_3, is reached, then $R = 7.95 \doteq 8.0$. All the data used to generate the R expression were ratings for the longitudinal axis with good dynamics in the lateral axis. In turn, the "best" dynamics were rated 2.0. If this 2.0 represented the lateral axis, then the total would be R + 2.0 = 10.0 maximum. Unfortunately, this reasoning leads one to conclude that a 6-axis task is rated 6.0 at best (perhaps it is, but data to support this contention are not available).

R_2: $R_2 = 2.5\,(T_{L_\theta}) \leq 3.25$

Fortunately, more effort has been expended on lead term effects than "normalized performance" effects, and the R_2 expression comes directly from Reference 7. If the smallest T_L data point and the next to largest T_L point in Figure 22, Reference 7, are joined by a straight line, this line intercepts the maximum pilot rating increment point at a lead of about 1.3 seconds. The maximum increment in rating is about 3.25 units, so

that $\quad R_2 = k(T_L)$, or $3.25 = k(1.3)$

and k = 2.5.

The use of a straight line approximation to the complete curve is for simplicity.

R_3: $R_3 = 1.0(T_{L_x}) \leq 1.20$

At first it might seem that R_3 should be the same as R_2. This just doesn't seem to fit the data. This may be due to the fact that the pitch loop (with T_{L_θ}) has a high bandwidth (cross-over frequency about 3 rad/sec, Reference 2) similar to the situation in which R_2 was obtained. However, the outer loop (with T_{L_x}) has a much smaller bandwidth of about 1 rad/sec. Perhaps maximum lead-generation-induced increments in rating are directly proportional to the bandwidth of the loop in question (in this case 1/3 of the R_2 maximum increment of 3.25 is about 1.10, or very close to the observed T_{L_x} -induced-increment maximum of about 1.20). On the other hand, considering the full longitudinal-lateral case, four lead terms can be generated. If two of these follow the Reference 7 data for the high frequency loop, and performance is not considered, then maximum pilot rating for the second two leads can be found from the maximum rating of 10.0 as:

$$PR = 10 - 2(3.25) - 1.0$$

$$= 2.50$$

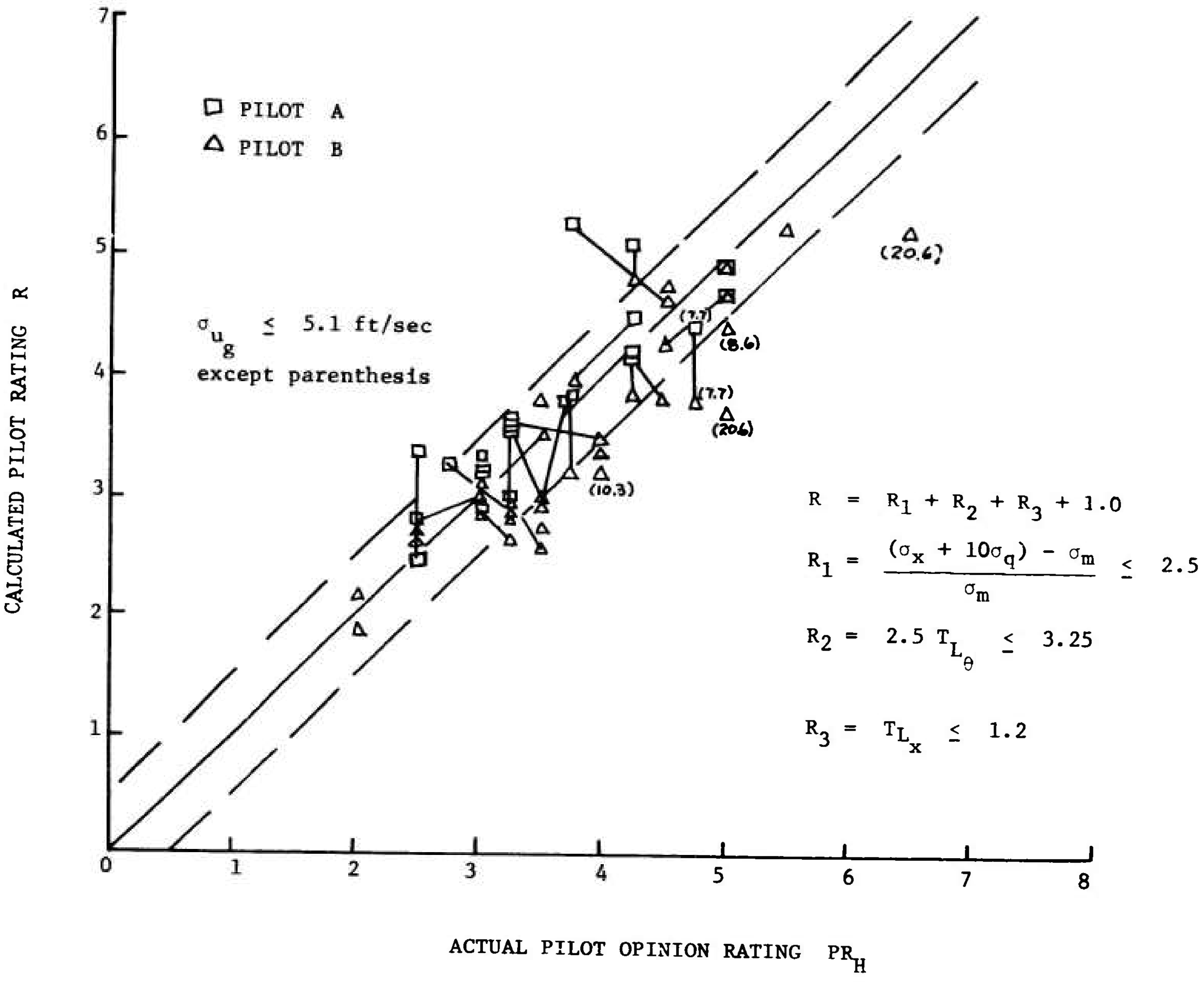
This "leaves" a value of 1.25 as maximum increment for each of the two low bandwidth loops, and <u>any stable</u> performance might be acceptable under these conditions (i.e., $R_1 = 0$).

In any event, the maximum increment in pilot rating is considered to occur at about the same value of lead as in R_2, so the unity coefficient on the R_3 term is used.

Bias: $R = R_1 + R_2 + R_3 + 1.0$

The unity addition to form the final rating expression is simply a result of the rating scales used to collect all of the data (see Reference 2). A rating of 1.0 is described as "excellent, includes optimum," and therefore becomes, for the most part, a lower bound on the numerical rating. In short, with no lead generation and adequate performance, R = 1.0.

In summary, the rating expression is reasonable, provides an excellent fit to the data, and raises several questions summarized above that could be resolved with very limited effort. No claim is made that a better "fit" could not be accomplished. It appears, however, that this general approach is not only promising for other tasks, but usable for hovering as it now stands. The former aspect is discussed in Section V; the latter is substantiated further in Section IV.



$$R = R_1 + R_2 + R_3 + 1.0$$

$$R_1 = \frac{(\sigma_x + 10\sigma_q) - \sigma_m}{\sigma_m} \leq 2.5$$

$$R_2 = 2.5\, T_{L_\theta} \leq 3.25$$

$$R_3 = T_{L_x} \leq 1.2$$

Figure 1. Pilot Rating vs R

TABLE I -- BASIC DATA

Data Source: AFFDL-TR-67-152

Case	Pilot	M_{u_g}	X_u	M_q	M_θ	σ_{u_g}	R_1	R_2	R_3	R	PR_h	Augmented System
PH1	A	0.67	0	-3	0	5.1	0.16	0.45	0.82	2.43	2.50	Rate System
	B	↓		↓	↓	↓	-	0.68	0.91	2.59	2.50	↓
PH2	A		-.05				0.59	0.48	0.73	2.80	2.50	
	B						0.59	0.55	0.88	3.02	3.00	
PH3	A		-.1				1.29	0.40	0.49	3.18	3.00	
	B						0.96	0.45	0.39	2.80	3.25	
PH4	A		-.2				2.5 2.70	0.33	0.66	4.49	4.25	
	B						2.21	0.40	0.35	3.96	3.75	
PH5	A		-.3				2.5 4.29	0.35	0.84	4.69	5.00	
	B						2.5 3.46	0.50	0.26	4.26	4.50	
PH6	A	0	-.1	-3	0	5.1	1.23	-	0.79	3.02	3.25	
	B		↓	↓	↓	↓	.825	.015	0.72	2.56	3.50	
PH7	A	0.33					1.31	0.20	0.78	3.29	2.75	
	B						1.10	0.25	0.53	2.88	3.25	
PH8	A	0.67					1.49	0.33	0.54	3.36	3.00	
	B						1.08	0.40	0.49	2.97	3.00	
PH9	A	1.00					1.50	0.58	0.85	3.93	3.75	
	B						1.20	0.50	0.50	3.20	3.75	
PH10	A	0.67	-.1	-1	0	5.1	1.68	1.08	0.39	4.15	4.25	Bare Air Frame
	B	↓	↓		↓	↓	1.19	1.25	0.41	3.85	4.25	
PH11	A			-3			1.46	0.33	0.44	3.23	3.00	Rate System
	B						0.98	0.43	0.41	2.82	3.00	↓
PH12	A			-5			1.18	0.08	0.66	2.92	3.00	
	B						0.91	0.13	0.56	2.60	3.25	
PH13	A	0.67	-.1	-3	0	2.6	0.64	0.55	1.2 1.58	3.39	2.50	Rate System
	B	↓	↓		↓		0.40	0.35	0.94	2.69	2.50	↓
PH15	A					5.1	1.48	0.43	0.75	3.66	3.25	
	B						1.08	0.40	0.49	2.97	3.50	
PH16	A					7.7	2.42	0.43	0.55	4.40	4.75	
	B						2.03	0.45	0.31	3.79	4.75	

TABLE I -- BASIC DATA (Cont.)

Data Source: AFFDL-TR-67-152

Case	Pilot	M_{u_g}	X_u	M_q	M_θ	σ_{u_g}	R_1	R_2	R_3	R	PR_h	Augmented System
PH17	A	1.00	-.05	-1	0	5.1	1.54	1.30	0.37	4.21	4.25	Bare Airframe
	B	↓		↓	↓	↓	1.11	1.35	0.36	3.82	4.50	↓
PH18	A	↓	-.2	↓	↓	↓	2.5 3.36	1.10	0.34	4.94	5.00	↓
	B	↓		↓	↓	↓	2.5 3.19	1.18	0.28	4.96	5.00	↓
PH19	A	1.00	-.05	-1	-3	5.1	1.13	1.43	0.43	3.99	3.75	Attitude System
	B	↓		↓	↓	↓	1.45	1.40	0.33	2.92	3.50	
PH20	A	↓	-.2	↓	↓	↓	2.5 3.14	1.18	0.43	5.11	4.25	↓
	B	↓		↓	↓	↓	2.5 3.00	0.98	0.34	4.82	4.25	↓
PH21	A	↓	-.05	↓	↓	↓	0.85	1.38	0.41	3.64	3.25	↓
	B	↓		↓	↓	↓	0.91	1.25	0.33	3.49	4.00	↓
PH22	A	↓	-.2	↓	↓	↓	2.5 3.05	1.28	0.50	5.28	3.75	↓
	B	↓		↓	↓	↓	2.5 2.94	0.78	0.33	4.62	4.50	↓
PH23	A	0.67	-.1	-3	0	5.1	1.48	0.38	0.66	3.52	3.25	Rate System
	B						1.05	0.40	0.52	2.97	3.25	
PH24	B	0.31	-.15	-.2	0	5.1	1.98	1.55	0.22	4.74	4.50	Bare Airframe
PH25	B	0.31	-.15	-4.7	-2.35	5.1	1.70	-	0.22	2.92	3.00	Attitude + Rate
PH26	B	0.15	-.017	-.006	0	5.1	0.05	1.90	0.43	3.38	4.00	Bare Airframe
PH27	B	0.15	-.017	-4	-2	5.1	0.0	-	0.83	1.87	2.00	Attitude + Rate
PH28	B	1.00	-.05	-5	-8	5.1	0.35	0.18	0.61	2.14	2.00	Attotide + Rate
PH29	B	0.33	-.05	-3	0	10.3	1.31	0.48	0.42	3.21	4.00	Rate
PH30	B	1.33	-.2	-3	0	2.6	0.91	0.50	0.31	2.72	3.50	Rate
PH31	B	0.33	-.1	-1	0	5.1	1.15	1.15	0.51	3.81	3.50	Bare Airframe
PH32	B	0.33	-.025	-1	0	20.6	2.28	1.50	0.44	5.22	6.50	Bare Airframe
PH33	B	0.33	-.1	-3	0	5.1	1.21	0.33	0.60	3.14	3.00	Rate
PH34	B	0.33	-.025	-3	0	20.6	1.59	0.63	0.51	3.73	5.00	Rate
PH35	B	0.20	-.09	-1	0	8.6	2.06	1.00	0.34	4.40	5.00	Bare Airframe
PH36	B	0.80	-.36	-1	0	2.1	1.39	1.05	0.08	3.52	3.50	Bare Airframe

TABLE II -- OTHER MEASURED PILOT PARAMETER DATA

Data Source: AFFDL-TR-68-165

Case	Pilot	M_{u_g}	X_u	M_q	M_θ	σ_{u_g}	R_1	R_2	R_3	R	PR_h	Simulator
PH10	B	0.67	-.1	-1	0	5.1	2.10	2.05	1.2 1.24	6.35	5.00	NN-Moving
	↓	↓	↓	↓	↓	↓	2.5 4.05	1.00	0.81	5.31	7.00	NN-Fixed
	↓	↓	↓	↓	↓	↓	1.19	1.25	0.41	3.85	4.25	UARL-Fixed
PH11	↓	↓	↓	-3	↓	↓	1.80	0.63	1.2 1.66	4.63	4.00	NN-Moving
	↓	↓	↓	↓	↓	↓	2.5 3.64	0.53	1.2 2.22	5.23	5.50	NN-Fixed
	↓	↓	↓	↓	↓	↓	0.98	0.43	0.41	2.82	3.00	UARL-Fixed
PH12	↓	↓	↓	-5	↓	↓	1.83	0.88	1.2 3.60	4.91	3.00	NN-Moving
	↓	↓	↓	↓	↓	↓	2.5 3.56	-	1.2 2.15	4.70	5.00	NN-Fixed
	↓	↓	↓	↓	↓	↓	0.91	.125	0.56	2.60	3.25	UARL-Fixed

SECTION III

THE MINIMUM PILOT RATING ANALYSIS METHOD

The rating expression discussed in Section II is, in fact, based on a single data source; namely the results in Reference 2. Direct correlation with other V/STOL hover data is impossible because of a general lack of measured pilot parameters and closed-loop performance under gust disturbances.

On the other hand, if pilot parameters and closed-loop performance could be predicted, a number of other data sources might be used to further validate the rating expression. Although general hover trends have been predicted before (Reference 5), the current method requires quantitative predictions if quantitative comparisons with pilot rating are to be made. The following material describes how such a prediction analysis method was evolved.

A. Optimal Pilot Concept: The idea that the human operator adjusts his method of control to produce low frequency performance which ".... is optimum in some sense analogous to that of minimum mean-squared tracking error" (Reference 9) is not new. However, quantitative performance predictions using this idea are fairly scarce. Two recent applications, with promising results, are presented in References 10 and 11. In both cases, a fixed pilot form was assumed, and pilot parameters were adjusted to, indeed, minimize mean-squared error.

Other free-form (i.e.,no assumed pilot form) optimal pilot models have also been successful (Reference 12 and the references therein). Nonetheless, in each case which performance "error" should be minimized presents the biggest question. Fortunately, the rating expression developed in Section II suggests a natural performance index to minimize. That is, since pilot ratings appear to be directly related to σ, it seems natural to assume, as an extension of simpler task results, that $\sigma = \sigma_x + 10\sigma_q$ is to be minimized.

To investigate this approach, a simplified version of the fixed-form pilot model of Reference 2 was implemented on an analog computer (see Appendix A) along with the hover dynamics and gust simulation. Since this pilot model form was used directly to compute the pilot parameters in Section II, its use again was natural.

Figure 2 shows the variation in σ as a function of each of the four variable pilot model parameters, with the remaining three parameters held constant at a "nominal" value. The case in question is PH 5, of Reference 2. Also shown in the figure are: a) optimal, in a minimum σ sense, parameters ("opt"), and b) actual measured pilot parameters (pilot). The pilot gain K_{p_θ} is not shown because it represented an unstable situation with the other three parameters at their nominal values.

Preceding page blank

The next question is the selection of a set of four pilot parameters that form a prediction of how the pilot operates. Note that:

a) Measured pilot gain, $-K_{p_x}$, seems to fall short of the "opt" value by a small amount, perhaps representing a finite stability gain and phase margin (per adjustment rules in Reference 9). This reduced value of gain has little effect on performance.

b) Measured pilot pitch lead, T_{L_θ}, is also less than the optimal value. In this case, a fairly large performance penalty is evident due to the "off optimal" condition.

c) Measured pilot displacement lead, T_{L_x}, is slightly larger than optimal, but the performance variation with lead is very small in this region.

Based on these observations, the initial prediction ground "rules" emerged as follows:

a) select pilot gains that produce minimum values of σ with a reasonable gain margin (i.e., a small increase in gain will not produce excessively large σ values). In general, keep the gain as low as possible while still producing "good" performance.

b) select pilot lead terms as the optimal, if greater than 0.2 seconds, or as the smallest value that produces acceptable performance. The former evolved from an earlier rating expression that had a "dead-zone" in rating increment up to 0.2 seconds. This was later removed for simplicity.

Using the somewhat hazy rules, the "predicted" set of pilot parameters shown in Figure 2 was used to predict performance, rating, and approximate closed-loop bandwidths (ω_{c_x} and ω_{c_θ}). The latter were obtained from a strip chart recording (see Appendix A, Figure A-2) and served mainly to validate the analog simulation. A digital computer was also used to validate the analog computer performance (σ) values. The resulting values are shown on Figure 2, along with actual measured values.

Even though the "selection rules" are somewhat arbitrary, and the resulting selected pilot parameters do not exactly match measured values, the overall rating, performance, and pilot parameter values compare very well with measured data.

B. Minimum Rating Concept: Although the results shown in Figure 2 compare well with measured data, the selection of pilot lead terms remains "arty". Returning to the rating expression developed in Section II, one could interpret the expression as a mathematical statement of the pilot's desire to "achieve adequate performance (small σ) with a minimum of effort (small T_L's)." If this were indeed true, then a trade in T_L's vs performance,

σ, should be evident. That is, an increase in T_{L_θ} or T_{L_x} is "justified" only if the "pay off" in terms of better performance (lower σ) is great enough. Stated another way, the pilot may attempt to minimize his own rating of the vehicle dynamics by adjusting his parameters to minimize R !

This interesting, but unproven, concept was informally presented to several pilots. Most accepted the idea as quite reasonable. In any event, the concept can be used to provide a rigid method of selecting pilot leads.

From the basic rating expression note that for small changes in T_{L_θ}:

$$\Delta R = \left(\frac{\partial R}{\partial T_{L_\theta}}\right) \Delta T_{L_\theta} + \left(\frac{\partial R}{\partial \sigma}\right) \Delta\sigma$$

$$= \left(2.5\right) \Delta T_{L_\theta} + \frac{\Delta\sigma}{0.8}$$

If no change in rating results (i.e., an increase in T_{L_θ} increases R_2, but also improves performance thereby reducing R_1 by a similar amount) then ΔR is zero, and

$$\frac{\Delta\sigma}{\Delta T_{L_\theta}} = -2.0$$

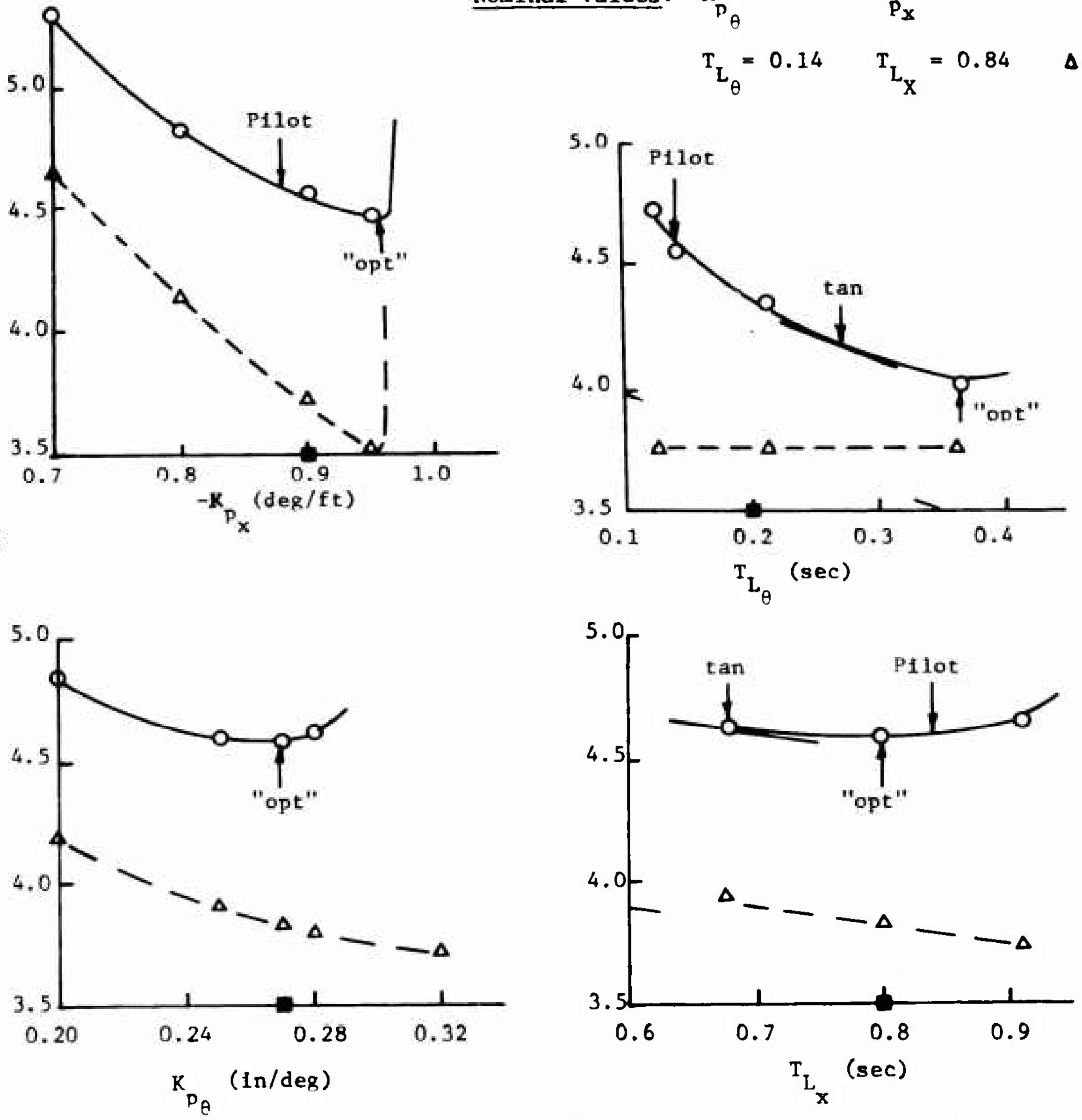
This "critical" slope in performance vs T_{L_θ} represents the point of minimum overall rating in respect to T_{L_θ}. If minimum rating is used as a pilot selection criterion, then the "predicted" T_{L_θ} is the value where $\Delta\sigma / \Delta T_{L_\theta} = -2.0$ (or $\Delta\sigma/\Delta T_{L_X} = -0.80$).

These "critical" slopes are shown in Figure 2. The tangent points (marked tan) with the true σ vs T_L curves are also shown. It can be seen that at least reasonable pilot leads are selected using this procedure, and it was decided to use the minimum rating and critical slope concept for all subsequent predictions. As will be seen in Section IV, this approach has yielded very good results in almost all cases.

In summary, the pilot-vehicle analysis method suggested above utilizes a fixed-form pilot model with pilot leads selected to give a minimum (best) pilot rating of the vehicle dynamics. Pilot gains are also selected to provide good closed-loop performance (and minimum rating) with a "reasonable" gain margin. In conjunction with the rating expression it has the unique capability, for the hover task, to allow the prediction of pilot parameters, closed-loop pilot-vehicle performance under gusty conditions, and pilot opinion rating. The procedure also provides a means of correlating the rating expression presented in Section II with V/STOL hover task data that do not include measured pilot parameters and closed-loop performance. It also suggests a method of specifying hover dynamic requirements that will be discussed later.

Nominal Values: $K_{p_\theta} = 0.28$ $-K_{p_x} = 0.88$ 0—0 $(\sigma_x + 10\sigma_q) = \sigma$

$T_{L_\theta} = 0.14$ $T_{L_X} = 0.84$ Δ—Δ σ_x



σ_x = Feet σ_q = RAD/Sec

■ = Predicted Value

$\sigma_{u_g} = 5.1$ FT/SEC

	PREDICTED	MEASURED
T_{L_θ}	0.20	0.14
$-K_{p_x}$	0.90	0.88
$K_{p\theta}$	0.27	0.38
T_{L_x}	0.78	0.84
σ_x	3.89	3.59
σ_q	0.055	0.064
ω_{c_θ}	2.33	2.40
ω_{c_x}	0.89	0.76
PILOT RATING	4.78	5.0

Figure 2. Initial Prediction Attempt

SECTION IV

CORRELATION OF PREDICTED RATINGS WITH DATA FROM VARIOUS SOURCES

Before leaving the data bank in Reference 2 (upon which the rating expression in Section II was developed) another correlation is of interest. That is Case PH 3 which was also evaluated with the addition of a first-order actuator simulation using different actuator time constants. Reference 2 does not include measured pilot parameters for the nonzero time constant cases, but the minimum rating prediction method developed in the last section may be used to evaluate the effects of the nonideal actuator. The results were as follows (Also see Table III, and the detailed analog computer results in Appendix A, Figures A-3 and A-4):

Case	τ_c	Pilot Rating	Completely Predicted Pilot Rating
PH 3	0.10	4.0	4.14
PH 3	0.50	6.0	5.93

This rather amazing correlation speaks for itself. The value of this approach in evaluating the effects of control system dynamics is also obvious.

Turning now to other data sources, Table IV lists the hover task data sources considered to date, along with additional pertinent information about each source. It can be seen that nearly a ten year time span is covered, along with a huge number of configurations that have been tested. More details on the first six sources may be found in compact form in Reference 5.

The complete prediction process using the analog computer is somewhat time consuming, making it impractical to correlate predicted ratings with <u>all</u> of the data in the eight sources in Table IV. Therefore, it was decided to select the best (lowest pilot rating) case and the "worst" (highest pilot rating) case from the summarized data in Appendix B of Reference 5 for the first six sources. The one exception was for the A'Harrah "Translation Stab" data where, while not quite the "best," what was thought to be the largest X_u case was considered (a later review of the data indicated, however, that a still larger valued X_u case was actually simulated). Best, intermediate, and worst cases were also selected from Reference 3. Finally, there are three configurations in Reference 4 where fixed base <u>and</u> moving base data are available. The configurations were the same except for M_q and control sensitivity, so that the extreme cases in M_q were considered. Hopefully, the control sensitivity difference did not affect pilot rating.

Preceding page blank

Predicted pilot ratings for the longitudinal dynamics, actual pilot ratings, and other specific details are given for each of these cases in Table III. Figures A-5 through A-18 in Appendix A contain detailed analog computer results for each case. Finally, each of the fifteen cases is discussed briefly in the following paragraphs. If a data source did not include a simulated, or actual, gust intensity, predictions were made at several levels. For the zero gust cases, the finite gust expressions for R_2 and R_3 were maintained, and R_1 taken as zero.

McCormick Case 113: This case represents a "best" rating (lowest numerical rating value) configuration with very good correlation between the predicted rating and two different pilot ratings (See Table III). One pilot stated, "Precision hover was very easy to fly." Note that no pitch loop lead is necessary, which would suggest a similar comment.

McCormick Case 126: This "intermediate" case also gave predicted results that match very well with two different pilot ratings. One pilot said it was "Difficult to maintain a hovering position...." This seems to correlate with the large (near maximum) R_1 performance term in the predicted rating.

McCormick Case 124: Both rating pilots gave this configuration a solid 8.0. Both, in turn, mentioned excessive pitch changes. One also stated "Ability to stop at the corners and hover precisely not great. Quite a bit of drifting in all directions." The predicted rating of 4.7 is, however, much lower in value, with the main contribution due to the R_2 (pitch lead) term. The correlation here, both in pilot comments and numerical rating, is very poor. No really good explanation exists, but one pilot did complain about height control and stated that "Lateral dynamics did have some effect on the evaluation". Nevertheless, correlation for this case is poor.

Breul Case 8: The actual ratings for the two different gust intensities seem to be inverted (i.e., the small gust input case is rated worse than the large gust input case) and perhaps the raw data in Reference 13 are in error. In any event, the predictions may be viewed as: a) at best, accurate enough to locate typographical errors in moving base data, b) at worst, accurate to within about one rating unit.

The prediction of pilot parameters (Section III) involves a "manual gradient" method to minimize the predicted pilot rating. Strictly speaking, this process should be repeated, using the first "predicted" values as the new "nominal" values until the "predictions" are the same as the "nominals." Time did not permit iterations of this type in most cases, and predictions were considered "valid" if they were generally "close" to the nominal values given in each figure. However, as a trial example the "best of Breul" case was carried through for four iterations. The last of these is shown in Figure A-8. It can be seen that the final predictions are very close to the nominal values; in fact, probably within analog accuracy for the σ computations. The following table indicates how the pilot parameters converged to the final values:

Step	$-K_{p_x}$	K_{p_θ}	T_{L_θ}	T_{L_x}	R
Original "Guess"	1.8	0.25	0.76	0.28	3.51
First Prediction	2.0	0.24	0.50	0.27	3.05
Second Prediction	1.75	0.27	0.36	0.33	2.76
Third Prediction	1.50	0.26	0.36	0.26	2.84
*Final Prediction	1.75	0.27	0.33	0.25	2.66

The first prediction is fairly close to the final, and as long as no more than one parameter varies greatly from "nominal" to "predicted" the first prediction should be fairly accurate.

Breul Case 4: As can be seen in Table III, the predictions correspond remarkably well with moving base simulator data for this "worst case". It should also be noted that T_{L_θ} for the second prediction is taken as the value that minimizes σ, since the critical slope tangent point is at a value of T_{L_θ} that produces a maximum R_2 term (See Figure A-8). Therefore, in keeping with the idea of pilot parameters that minimize R, the lead term becomes as large as necessary, within human limitations, to minimize the R_1 performance term. The idea of minimum pilot rating leads to a very good prediction for this case.

Seckel Case 43: The best and the worst ratings, from the summary of this data source in Reference 5, were obtained with the same configuration only with different magnitudes of simulated gust inputs to a variable stability helicopter. Although the higher gust level input prediction is optimistic by about one rating unit, the lower gust level prediction is again amazingly accurate. In the former case, the limit on the R_1 term prevents a better match, although this limit was necessary to fit the original fixed base simulator data shown in Figure 1. Perhaps the limit should be slightly higher.

A'Harrah Case 47: Unfortunately this data source, for fixed base simulator results, is not very specific. The pilot (Reference 14) ratings came from evaluations which:

> "...were conducted primarily in hover flight...(and)...were then verified at discrete speeds during transition and in continuous transition."

and were

---

* = Nominal values of pilot gains were returned to the 2nd prediction values, since third predicted rating increased.

"...rated...by evaluating the dynamic and control characteristics in still air and then giving an overall rating...in slightly turbulent air (5 ft/sec rms)."

Thus, exactly which vehicle characteristics were being evaluated (hover or transition), and under what conditions (no gust or 5 ft/sec), remains unknown. The best rated case results are shown in Figure A-11, and perhaps the pilot did have precision hover, with turbulence, in mind for his rating corresponds very well with the prediction. A very similar fixed base case was tested and reported in Reference 2. The measured pilot parameters for this case are shown for comparison with the predicted values. The agreement is quite good.

A'Harrah Case 55: The results for this case are shown in Figure A-12. This is both A'Harrah's worst case and the author's, since it has a predicted rating of nearly three rating-units lower than the actual pilot rating. As in the worst Seckel case, the limit on R_1 again holds the predicted rating down (See Table III). Or, see the discussion for Case 47, transition dynamics were perhaps dominant in the actual rating. In any event, the correlation is very poor.

Madden Data No 1: Unfortunately, the author does not have these fixed base data, Reference 17, and very few specifics are available (See Table IV). The results for the best case are shown in Figure A-13 and Table III. All that can be said is that for small gust input levels the predictions are very close to the actual rating, but actual gust inputs, if any, are unknown. It should also be noted that this case represents attitude stabilization.

Madden Data No 2: This worst case is quite interesting. Nominal pilot model parameters that provide a stable hover closed-loop system could not be found for this 6.0 rated configuration.* Therefore, a first prediction is "unflyable," yet the pilot probably did, indeed, hover the simulated aircraft. Some explanation is therefore in order. Reference 5 indicates that in this case the augmented aircraft (with an attitude stabilization system) has a positively damped, stable, oscillatory characteristics plus a slightly unstable first order divergence with a time constant of about 7.7 seconds. Since this divergence is quite slow, it is very possible that the pilot simply "hangs on," putting in trim-like control motions to check the gradual divergence. In this case the continuous tracking, precision hover, pilot model upon which the rating prediction is based is simply no longer valid.

Unfortunately, pilot comments for this case are not available. However, two points should be made here. First, the "failure" of the prediction method in this case is, in respect to flying qualities specification (to be discussed in detail later in Section V), actually a "success." This will be explained later.

As a result this case does not appear in Table III.

Secondly, as a matter of curiosity, the pilot model time delay used for all the hover predictions was reduced to 0.40 seconds, and Madden No 2 was again "flown." Surprisingly, the predicted rating for this case with a gust rms intensity of 3.0 ft/sec was a sound 3.5 compared to the actual rating of 6.0! This sensitivity to time delay was not only unsuspected, but rather frightening in view of the excellent correlation in ratings found using a constant 0.44 second value for all of the other cases. However, as discussed in Section V, this aspect can perhaps also be exploited. This possibly misleading special case is not shown in Table III.

Shaw Data No 2: This case is one of the most interesting correlations attempted because three different evaluations of the same, or very similar, configuration are available, namely: a) complete prediction, b) fixed base simulator data with measured pilot parameters, and c) flight test data. The results, Figure A-14, show very good rating agreement between predictions for gust inputs up to 6 ft/sec and the Shaw flight test results. Also, the predicted rating, performance, and pilot parameters compare well with fixed base data from Reference 2. Perhaps it would be unreasonable to expect any better correlation.

A'Harrah Data No 11: This case, and the next, represents a "translational stabilization system" per Reference 5 (very large X_u values). The results are shown in Figure A-15. Unfortunately, as discussed under Case 47, there is some question as to what characteristics the pilot was rating, and what level of gust input was involved. If the pilot rated the low gust magnitude input case, the predictions are in good agreement with the actual ratings. For higher level gust inputs, the prediction is a little over one and one-half rating units high. (Reference 5 indicates "...a greater percentage of testing was done without turbulence.")

A'Harrah Data No 15: The worst case is, indeed, poor with a pilot rating of 8.5. The prediction results are shown in Figure A-16. Predicted performance is so poor that the gust input magnitude has little effect, and the prediction is a generally unacceptable rating of 6.75. Again, the prediction is numerically lower than the actual rating because of the limit on the R_1 term.

Vinje Cases PH 10 and PH 12: For these two configurations, with different M_q values, both fixed base and moving base ratings from the same pilot are available. In addition, measured pilot parameters have been computed. These results are compared with predicted results in Figures A-17 and A-18. Results in both cases are very similar: a) fixed base, moving base, and predicted ratings are in very good agreement, b) predicted $-K_{p_x}$ values are somewhat larger than measured, c) predicted K_{p_θ} and T_{L_θ} values are between the fixed and moving base values, d) predicted T_{L_x} values match the fixed base data very well, but the moving base values are much larger, e) the performance predictions compare quite well with measured values.

In summary, the correlation of predicted ratings and actual ratings from fixed base, moving base, and flight test is very good. The largest differences appear with high rating cases in general, and the A'Harrah fixed base data in particular. Better correlation would result in these cases, if the upper limit on the R_1 term were increased.

The results for Vinje PH 10 and PH 12 cases also shed some light on the differences between predicted and actual ratings for the NM data presented in Section II. Since measured x-loop lead terms were much higher than predicted or fixed base values, the R_3 term would be much larger for predictions using <u>measured</u> moving base data. In fact, the resulting predictions would be about one rating unit larger and produce the "error" shown in Table II. This is an interesting result in itself, and is perhaps due to motion cues that, in effect, reduce the coefficient on the R_3 term.

It would be difficult to categorically say the rating prediction method has "failed" in any attempted application to date. However, if "failure" is an "error" of one rating unit or more, then the following cases, with potential explanations, remain unresolved:

Case	Explanation (?)
PH 32 (Ref 2)	Gust input greater than 5 ft/sec
PH 34 (Ref 2)	Gust input greater than 5 ft/sec
PH 22 (Ref 2) Pilot A	Pilot B within 0.12 units for same configuration
Case 124 (Ref 3)	Quite similar cases (123 and 127) were rated from 2 to 6 in comparison with predicted 4.66 for this case
Seckel 43, Worst	Gust input greater than 5 ft/sec
A'Harrah Case 55	Uncertain as to what was rated
A'Harrah Data No 11	Uncertain as to what was rated
A'Harrah Data No 15	Uncertain as to what was rated
PH 10 NM (Measured Pilot Parameters)	See above paragraphs
PH 12 NM (Measured Pilot Parameters)	
PH 10 NF (Measured Pilot Parameters)	Same configuration gave good correlation in UARL simulation (Fig A-17)

Even ignoring the above "explanation," these cases represent only a few of those considered:

Source	Cases Considered
UARL Fixed Base	59
Northrop Moving Base	6
Northrop Fixed Base	3
Breul Moving Base	4
Seckel Var Stab Helicopter	2
A'Harrah Fixed Base	4
Madden Fixed Base	2
Shaw Flight Test	1
	81

TABLE III Correlation of Predicted and Actual Ratings

Case	M_{u_g}	X_u	M_q	M_θ	σ_{u_g}	R_1	R_2	R_3	R	PR_h	Comments
Data Source: AFFDL-TR-67-152, Miller											
PH3	.67	-.1	-3	0	5.1	1.79	.75	.60	4.14	4.0	$\tau_c = 0.1$
"	"	"	"	"	"	2.5 3.25	1.53	.90	5.93	6.0	$\tau_c = 0.5$
Data Source: NOR-69-7, McCormick											
113	1.0	-.05	-6.35	-2.27	3.4	.73	0	.95	2.68	3.0/1.5	Moving
126	.33	-.2	-1.8	-1.21	3.4	2.43	.50	.53	4.46	4.5/5.0	Base
124	.33	-.2	-.8	-1.25	3.4	1.01	2.13	.52	4.66	8/8	
Data Source: AFFDL-TR-67-179, Craig											
Breul 8	0.47	-.1	-1.33	0	3.0	.58	.83	.25	2.66	4.0	PR_h inverted?
"	"	"	"	"	6.0	2.15	"	"	4.23	3.0	Moving Base
Breul 4	0.74	-.1	0	0	3.0	1.45	3.25 4.0	.32	6.02	6.2	
"	"	"	"	"	6.0	2.50 3.90	"	"	7.07	7.0	
Seckel 43	3.40	-.15	-1.98	0	.52	0	1.94	.24	3.18	3.2	Variable Stability Helicopter Simulated gust
"	"	"	"	"	6.3	2.50 7.90	"	"	5.68	6.6	
A' 15	5.15	-1.88	-.075	0	0.5	2.50 3.29	3.25 12.5	0	6.75	8.5	Fixed Base
H 47	1.29	-.23	-5.1	0	5.0	2.50 2.62	.31	.23	4.04	3.8	
A "	"	"	"	"	0	0	.31	.23	1.53	3.8	Flew
R 55	2.56	-.24	-1	0	5.0	2.5 7.71	2.00	.15	5.65	8.5	1.)No Gust
R "	"	"	"	"	0	0	2.00	.15	3.15	8.5	2.)σ_{u_g} = 5.0
A 11	2.40	-3.9	-.35	0	5.0	2.5 2.6	2.00	0	5.5	3.8	3.)Rated"overall"
H "	"	"	"	"	0	0	2.00	0	3.0	3.8	
Madden 1	0.11	-.126	-1.0	-24	0	0	0	.30	1.3	2.0	Fixed Base
"	"	"	"	"	3.0	1.5	0	.30	2.8	2.0	Gust Unknown
Shaw 2	.322	-.153	-4.9	-2.4	0	0	.09	.375	1.47	2-3	XC-142 Flight
"	"	"	"	"	3	.38	"	"	1.85	2-3	Test
"	"	"	"	"	6	1.75	"	"	3.22	2-3	Gust Unknown
Data Source: AFFDL-TR-68-165, Vinje											
PH10	0.67	-.1	-1	0	5.1	1.68	1.90	.40	4.98	4.25	Fixed Base
"	"	"	"	"	"	"	"	"	4.98	5.00	Moving Base
PH12	0.67	-.1	-5	0	5.1	.92	.53	.56	3.01	3.25	Fixed Base
"	"	"	"	"	"	"	"	"	3.01	3.00	Moving Base

NOTE: The gust intensities for the A'Harrah, Madden, and Shaw data were assumed, also ω_b = .314 rad/sec was used for all predictions.

Source	Case/Data *	Reference	System	Gust Spectrum	ω_b (Rad/sec)	σ_{ug} (Ft/sec)	Task	Configurations	No. of Pilots	Rating Scale	Test Conditions/Remarks
Breul Feb 1966	8	13	Conventional	D-LA	.09	3/6	Hover-Translate-Hover	450	3	C	Moving base in pitch & roll Motion display
	4	13	"		.09	3/6					
Seckel Dec. 1961	43	15	Conventional	D-LO	.314	.52/ 6.3	Hover-Translate-Hover plus hoop pick-up	U	5	C	Var. Stab. Helicopter
A'Harran July 1961	47	14	Conventional	U	U	5.0	Mainly hover. Still air-gust-overall rating	220	8	C	Fixed base TV terrain display
	55	14	"								
Madden Aug 1960	1	17	Attitude Stab	U	U	U	Unknown	U	U	U	Fixed base
	2	17	" "								
Shaw	2	16	Att. Stab.	U	U	U	Unknown	U	U	U	XC-142 flt test. Probably low, or no gust inputs.
A'Harran July 1961	11	14	Trans. Stab.	U	U	5.0	Mainly hover, still air-gust-overall rating	220	8	C	Fixed base, TV terrain display
	15	14	" "								
Vinje Apr 1969	PH10 PH12	4 4	Conventional Rate Stab.	D-LO	.314	5.1	Precision hover	3	1	C	a) fixed base UARL, b) Norair fixed, c) Norair moving

U = Unknown
D-LA = Dryden lateral form
D-LO = Dryden longitudinal form
C = Cooper rating scale
* = Case/Data for first six sources follow the designations used in Reference 5.
CH = Cooper-Harper Rating Scale.

TABLE IV SOURCE SUMMARY

Source	Case/Data	Reference	System	Gust Spectrum	ω_b (Rad/sec)	σ_{ug} (Ft/sec)	Task	Configurations	No. of Pilots	Rating Scale	Test Conditions/Remarks
McCormick Apr 1969	113	3	Att.+ Rate	D-LO	.314	3.4	Various maneuvers including hover	124	6	CH	Moving base in pitch, yaw, and roll. Motion display.
	126	3	" "		.314	"					
	124	3	" "		.314	"					

U = Unknown

D-LA = Dryden lateral form

D-LO = Dryden longitudinal form

C = Cooper rating scale

CH = Cooper-Harper Rating Scale

TABLE IV SOURCE SUMMARY (Cont.)

SECTION V

APPLICATION TO OTHER TASKS, SPECIFICATIONS, AND CONTROL DESIGN

The minimum pilot rating analysis method developed in Section II, and evaluated in Section III, was, of course, developed for flying quality evaluations of hover dynamics. In some respects the method is "ideal" for this purpose since it:

a. does not require an assumed type of augmentation (i.e., rate, attitude, etc., systems),

b. accounts for control system and other higher order dynamics,

c. accounts for the effects of gust intensity (at least up to about 5 ft/sec rms), and

d. is extremely simple to use.

In respect to the latter point, the minimum rating method, along with the rating expression in Section II, has been programmed for an IBM 7090 digital computer (Reference 18). The program requires about one minute of machine time per configuration evaluated, and has given results that have excellent correspondence with actual pilot ratings for the precision hover cases in Reference 4. The machine output includes pilot model parameters, closed-loop performance in terms of standard deviations, and a predicted pilot rating. This computer program should not be confused with other pilot rating routines such as those discussed in Reference 19 and 20. The former, Reference 19, is basically a computer storage program from which a prediction, based on the extrapolation of a number of aircraft-like parameters vs pilot rating curves, is made. The program cannot cope with the effects of gusts, control system dynamics, etc., and has no capability to predict closed-loop pilot-vehicle performance.

The latter work, Reference 20, provides a mathematical rating expression for PIO tendencies, based on the pitch rate time history response to a step input. This approach has the same limitations as above; except for control dynamics.

Before turning to other tasks, the minimum rating method does have limitations, and potentials, in respect to hover. On the negative side, extension to further degrees of freedom (in this case height control and longitudinal plus lateral control) has not been attempted. While this extension is within the framework of the general development, it would require a more elaborate pilot model and additional data. Some longitudinal plus lateral data are available in Reference 3, but the other basic sources contain, for the most part, separate evaluations.

On the positive side, two interesting observations can be made. Both could lead to valuable extensions. First, the apparent sensitivity of rating to assumed pilot model time delay (See Madden Data No 2, Section IV) could be put to an interesting test. Reference 21 contains data on the variation in measured effective time delay between subjects, as well as within a subject. One such set of data (Figure 9 in Reference 21) indicates a difference of as much as 0.04 seconds between three subjects for zero input. The Madden 2 case results indicate that for a poor configuration (rated 6.0 by pilot) this difference could change a predicted rating from "unflyable" to "clearly adequate." It may be possible, to relate pilot rating differences to pilot reaction time delay differences through the minimum rating method, and perhaps explain part of the normally large rating spread at the poor end (see Reference 7).

Secondly, the rating expression could be extended to include a term that is a function of control sensitivity. In particular, the deviation of pilot gain, K_{p_θ} , from a "desired" value as indicated in Reference 2 could be used. Perhaps K_{p_x} has some secondary effect on rating also. In any event, extensions of this type appear to be quite natural.

A. Other Tasks: The application of the minimum rating method to other tasks seems to be quite feasible. The discussion in Section II shows good agreement between the hover task performance term, R_1, and Reference 7 data for an entirely different task. In turn, the R_2 term came from Reference 7 and was based on another controlled element and non-hover task. Therefore, perhaps the form of the rating expression is universal. If this is true, the "minimum rating" concept may also be widely applicable. Only different task studies will provide the answer.

Toward this end, the computer program in Reference 18 will be given a wide distribution. The approach used for the hover task can fit any precision tracking task. It is, therefore, relatively simple to study other tasks. Perhaps the only limitation is basic data with performance measures.

B. Specification: Appendix B contains a proposed addition, or alternate form, of "Hover and Low Speed Requirements" for Reference 1. In short, it allows the contractor to predict pilot rating using the rating expression in Section II and the minimum rating approach. Other limits on pilot leads and gain margins are included. The resulting predicted ratings must then meet certain minimum requirements. This approach has a number of advantages, most of which have already been covered in a-d above. Furthermore, the results in Section III serve to validate the requirement directly since predicted ratings match actual ratings quite well.

The biggest single objection to this approach seems to be that "compliance cannot be demonstrated through flight test." This is, indeed, true in the strictest sense, because it would require an "analog pilot model" plus "standard gust day" flying weather. Nonetheless, many alternate, but not exact, approximations to true flight test verification can be envisioned with a little imagination, and this task is, perhaps, best left for the flight test experts.

It has also been suggested that the whole approach be used to generate flying quality iso-opinion data to augment simulator results. Next, more suitable (in a flight test sense) criteria would be established. Certainly, there is nothing wrong with this idea, and the "Paper Pilot" (Reference 18) computer program is available for this and other uses. However, in the author's biased opinion this is much like telling a pilot to numerically rate a configuration and then "shut-up", since all that's wanted is a "simple" answer. The proposed approach goes much farther and is, in reality, quite simple in itself.

Finally, it should be noted that the Madden 2 Case discussed in Section IV, and rated 6.0 would not meet the proposed specification because of the required gain margin. It would, therefore, not meet Level 3 which is defined as a rating of $5.5 < R \leq 6.5$.

C. Control Design: Extension of the flying qualities evaluation application to control system design is direct and natural. Potentially, a large number of tentative control concepts can be rapidly evaluated without the need for complex manned simulation. The latter can subsequently be used to validate the results using a few final configurations. This is a more or less straightforward application; and the rating expression components suggest system improvements (e.g., large R_2 implies more pitch damping is required).

A more interesting possibility is to combine the minimum rating concept with modern optimal control theory to develop a design synthesis method that takes the pilot and his rating of the "effective" aircraft dynamics into account. Such a procedure would be extremely useful.

In summary, other applications appear to be not only possible, but the results may be extremely interesting and useful.

SECTION VI

SUMMARY AND CONCLUSIONS

An examination of the correlation of pilot rating with closed-loop performance and pilot model parameters has led to: a) a method of calculating pilot rating from measured data for the hover task, b) a new approach to pilot-vehicle analysis with potentially wide application that can provide "automatic" prediction of pilot model parameters, closed-loop performance, and pilot rating, and c) an entirely new approach to the evaluation and specification of flying qualities. These developments have been tested for only one task; VTOL hover. However, there is every indication that much wider application is possible both in terms of other tasks and uses.

The results reported here are far too good to represent an "accident." Perhaps the gap between flying qualities and human response theory is now a lot smaller. Or, maybe the hover task is a rare exception, and what now appears to be a widely applicable approach is, instead, of limited value. In any event, the author feels that the art of specifying and evaluating flying qualities will never be quite the same again.

Preceding page blank

REFERENCES

1. Chalk, C., et al, "V/STOL Flying Qualities Criteria Development: Vol. I. A Proposed Military Specification for V/STOL Flying Qualities", Cornell Aeronautical Laboratory, Inc., October 1968.

2. Miller, D. P. and Vinje, E. W., "Fixed-Base Flight Simulator Studies of VTOL Aircraft Handling Qualities in Hovering and Low-Speed Flight", United Aircraft Research Laboratories, AFFDL-TR-67-152, January 1968.

3. McCormick, Ralph L., "VTOL Handling Qualities Criteria Study Through Moving-Base Simulation", Northrop Corporation, Report NOR-69-7, April 1969. (Also AFFDL-TR-69-27)

4. Vinje, E. W., and Miller, D. P., "Analytical and Flight Simulator Studies to Develop Design Criteria for VTOL Aircraft Control Systems", United Aircraft Research Laboratories, AFFDL-TR-68-165, April 1969.

5. Craig, S. J., and Campbell, A., "Analysis of VTOL Handling Qualities Requirements", Part I, Systems Technology, Inc., AFFDL-TR-67-179, October 1968.

6. Teper, G. L., and Jex, H. R., "Synthesis of Manned Booster Control Systems Using Mathematical Pilot Models", Systems Technology, Incorporated, Sixth Annual Symp. Prof. Group on HF in Electronics, IEEE, 6-8 May 1965.

7. McDonnell, John D., "Pilot Rating Techniques for the Estimation and Evaluation of Handling Qualities", Systems Technology, Inc., AFFDL-TR-68-76, December 1968.

8. Magdaleno, Raymond, and Wolkovitch, Julian, "Performance Criteria for Linear Constant - Coefficient Systems with Random Inputs", Systems Technology, Inc., ASD-TDR-62-470, January 1963.

9. McRuer, D. T., et al, "Human Pilot Dynamics in Compensatory Systems", Systems Technology, Inc., AFFDL-TR-65-15, July 1965.

10. Wanamaker, J. E., and Sower W. A., "Extension of Pilot Describing Functions to Multiple Compensatory Tracking Tasks", GE/EE/69-18, Air Force Institute of Technology, March 1969.

11. Mannen, J. T., and Duggar, L. C., "Development of Human Describing Function Models for Nonlinear Control Elements", GE/EE/69-6, Air Force Institute of Technology, March 1969.

Preceding page blank

12. Elkind, J. I., et al, "An Optimal Control Method for Predicting Control Characteristics and Display Requirements of Manned-Vehicle Systems", Bolt Beranek and Newman Inc., AFFDL-TR-67-187, June 1968.

13. Breul, H. T., "A Simulator Study of Low Speed VTOL Handling Qualities in Turbulence," Grumman Aircraft Engineering Corporation, Research Report RE-238, February 1966.

14. A'Harrah, R. C., and Kwiatkowski, S. F., "A New Look at V/STOL Flying Qualities", Aero Eng., Vol. 20, No. 7, July 1961.

15. Seckel, E., Traybar, J., and Miller, G. E., "Longitudinal Handling Qualities for Hovering", Princeton University, Department of Aeronautical Engineering, Report No. 594, December 1961.

16. "Development of VTOL Handling Qualities Design Criteria", CAL Summary of Notes from VTOL Meetings at Wright Field, 10-24 October 1966.

17. Madden, J., Kroll, J., and Neil, D., "A Study of VTOL/STOL Flying Qualities Requirements", Bell Aircraft Corporation, Report 2023-917001, 10 August 1969.

18. Dillow, James D., "The Paper Pilot - A Digital Computer Program to Predict Pilot Rating for the Hover Task", FDCC TM-69-3 December 1969. (To be published as AFFDL-TR-70-40).

19. Taylor, Lawrence W., "Fixed Base Simulator Pilot Rating Surveys for Predicting Lateral-Directional Handling Qualities and Pilot Rating Variability", NASA TN D-5358, August 1969.

20. Eichler, J., "A Regression Analysis of Pilot-Induced Oscillation Ratings", Grumman Research Department Memo RM-444, May 1969.

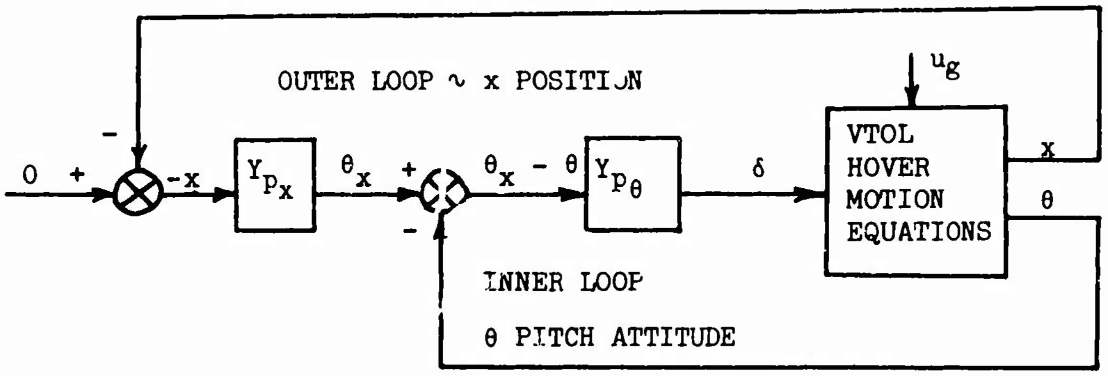
21. Jex, H. R., McDonnell, J. D., and Phatak, A. V., "A Critical Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time", Systems Technology, Inc., NASA CR-616, November 1966.

22. Adams, J. J., "An Approach to the Determination of Aircraft Handling Qualities Using Pilot Transfer Functions", presented at the Fourth NASA Inter-Center Control Systems Conference, November 4-5, 1969, Cambridge, Mass.

APPENDIX A

ANALOG COMPUTER PROGRAM AND RESULTS

The hovering task model equations used in the analog simulation were adapted from Appendix B of AFFDL TR 67-152 (Reference 2). Open-loop equations for pitch attitude and position response to control inputs and turbulence were programmed on an analog computer. The loop closures with pilot models were in the manner of Reference 2 as represented in the sketch below,



where Y_{p_x} and Y_{p_θ} are the pilot models for the x and θ loops respectively.

A. VTOL HOVER MOTION EQUATIONS

The general form of the linearized equations of motion which describe the VTOL hover motion in response to control inputs and turbulence is

$$M_u u + M_\theta \theta + M_q q - \dot{q} = -M_\delta \delta - M_u u_g$$

$$X_u u - g\theta - \dot{u} = -X_\delta \delta - X_u u_g$$

After converting radian measure to degrees for analog computer scaling and rearranging to solve for highest order terms, the equations are

$$\dot{\bar{q}} = |57.3M_u|(u + u_g) - |M_\theta|\bar{\theta} - |M_q|\bar{q} + 57.3\, M_\delta \delta$$

$$\dot{u} = -|X_u|(u + u_g) - (g/57.3)\,\bar{\theta}$$

where the bars denote angular measures in degrees. The longitudinal acceleration due to a stick command, X_{δ_e}, is usually zero for nonrotary-wing VTOL aircraft. The signs of the coefficients for the conditions to be investigated are accounted for in the above equations.

B. TURBULENCE INPUT u_g

Turbulence is represented as a random gust velocity, u_g, in the x direction with the spectral shape

$$\Phi_{u_g u_g}(\omega) = \frac{2\omega_b \sigma_{u_g}^2}{\omega^2 + \omega_b^2} \qquad \omega_b = 0.314 \text{ rad/sec}$$

$$\sigma_{u_g}^2 = \frac{1}{2\Pi} \int_{-\infty}^{+\infty} \Phi(\omega)\,d\omega$$

Since the input gust is assumed to have a Gaussian amplitude probability distribution with zero mean, and the vehicle equations are linear, an "equivalent deterministic input" can be used.

This equivalent deterministic input (or transient analog) is obtained (Reference 8) by the following expression for spectral density

$$\Phi_{u_g u_g}(s) = \left|U_g(s) U_g(-s)\right|_{s = j\omega} = \left|\frac{u_g(0)}{s+\omega_b} \cdot \frac{u_g(0)}{-s+\omega_b}\right|_{s = j\omega}$$

$$\text{where } u_g(0) = \sigma_{u_g}\sqrt{2\omega_b} \cdot$$

$$\text{Therefore } U_g(s) = \frac{\sigma_{u_g}\sqrt{2\omega_b}}{s+\omega_b}$$

$$\text{and } u_g(t) = \sigma_{u_g}\sqrt{2\omega_b}\, e^{-\omega_b t}$$

represents the specific deterministic input to represent the gust spectra in question. With this input, the integral of any squared parameter of interest (e.g., x, q, θ) becomes the variance of that parameter when steady-state conditions are reached.

This method of gust representation is especially well suited to fast time repetitive operation on the analog computer, since no time averages or repeated trials are required to obtain "exact" results.

C. PILOT MODELS

The pilot models used in TR 67-152 were simplified as follows:

$$Y_{p\theta} = \frac{K_{p\theta}(T_{L\theta}\, s+1)e^{-\tau_\theta s}}{T_N\, s+1} \doteq K_{p\theta}(T_{L\theta}\, s+1)e^{-\tau s}$$

where

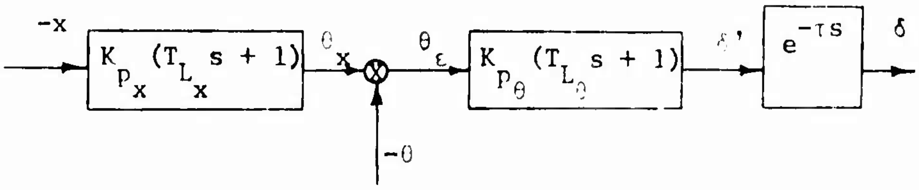
$$\tau \doteq \tau_0 + T_n = .09 + .35 = .44$$

and

$$Y_{p_x} = K_{p_x}(T_{L_x} s + 1)e^{-\tau_x s} \doteq K_{p_x}(T_{L_x} s + 1)$$

when $\tau_x \doteq 0$

The block diagram representation of the pilot models is shown below: (the bar notation to denote degrees is now omitted for simplicity)



The equations which were programmed are ($K_{p_x} \leq 0$)

$$\theta_x = K_{p_x} T_{L_x} \dot{x} + K_{p_x} x = K_{p_x} T_{L_x} u + K_{p_x} x$$

$$\dot{\theta}_x = K_{p_x} T_{L_x} \ddot{x} + K_{p_x} \dot{x} = K_{p_x} T_{L_x} \dot{u} + K_{p_x} u$$

$$\theta_\varepsilon = \theta_x - \theta$$

$$\dot{\theta}_\varepsilon = \dot{\theta}_x - \dot{\theta}$$

$$\delta' = K_{p_\theta} T_{L_\theta} \dot{\theta}_\varepsilon + K_{p_\theta} \theta_\varepsilon$$

The time delay $e^{-\tau s}$ is modeled by the Pade' approximation.

$$\frac{\delta}{\delta'} = e^{-\tau s} \doteq \frac{-(s - 2/\tau)}{(s + 2/\tau)}$$

$$\frac{d\delta}{dt} + [2/\tau]\delta = \frac{-d\delta'}{dt} + [2/\tau]\delta'$$

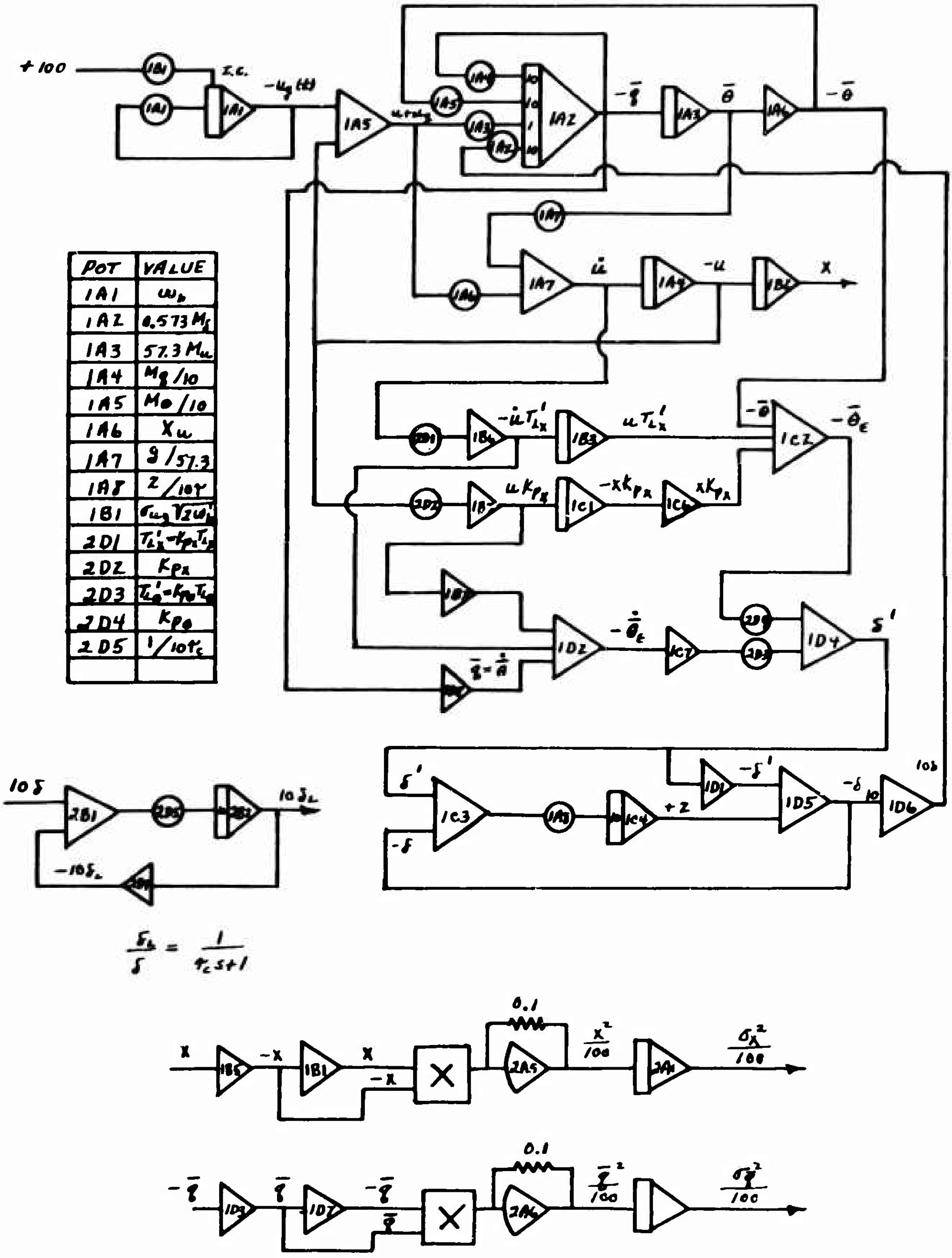
$$\frac{d}{dt}[\delta + \delta'] = \frac{2}{\tau}[\delta' - \delta]$$

let $Z = \delta + \delta'$

then $\dot{Z} = [2/\tau](\delta' - \delta)$

$$\delta = Z - \delta'$$

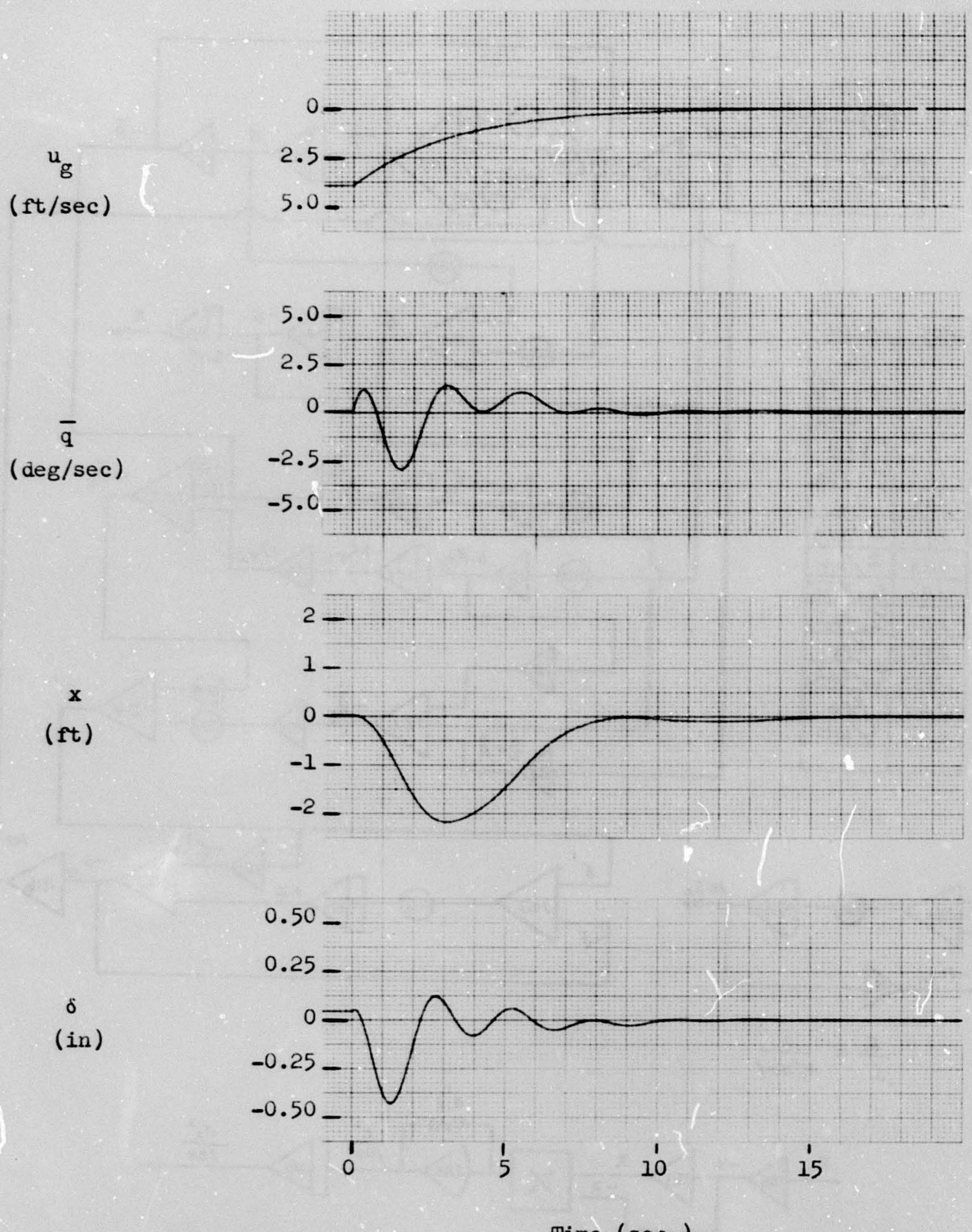
The analog programs are shown in Figure A-1.



POT	VALUE
1A1	ω_b
1A2	$0.573 M_\delta$
1A3	$57.3 M_u$
1A4	$M_q/10$
1A5	$M_\theta/10$
1A6	X_u
1A7	$g/57.3$
1A8	$2/10\tau$
1B1	$\sigma_{u_g}\sqrt{2\omega_b}$
2D1	$T'_{Lx}-K_{px}T_{Lx}$
2D2	K_{px}
2D3	$T'_{L\theta}-K_{p\theta}T_{L\theta}$
2D4	$K_{p\theta}$
2D5	$1/10\tau_c$

$$\frac{\delta_L}{\delta} = \frac{1}{\tau_c s+1}$$

Figure A-1. Analog Computer Circuits



Case PH 5 $K_{p_x} = -0.90$, $K_{p_\theta} = 0.27$, $T_{L_\theta} = 0.20$, $T_{L_x} = 0.78$

Figure A-2. Transient Analog Responses

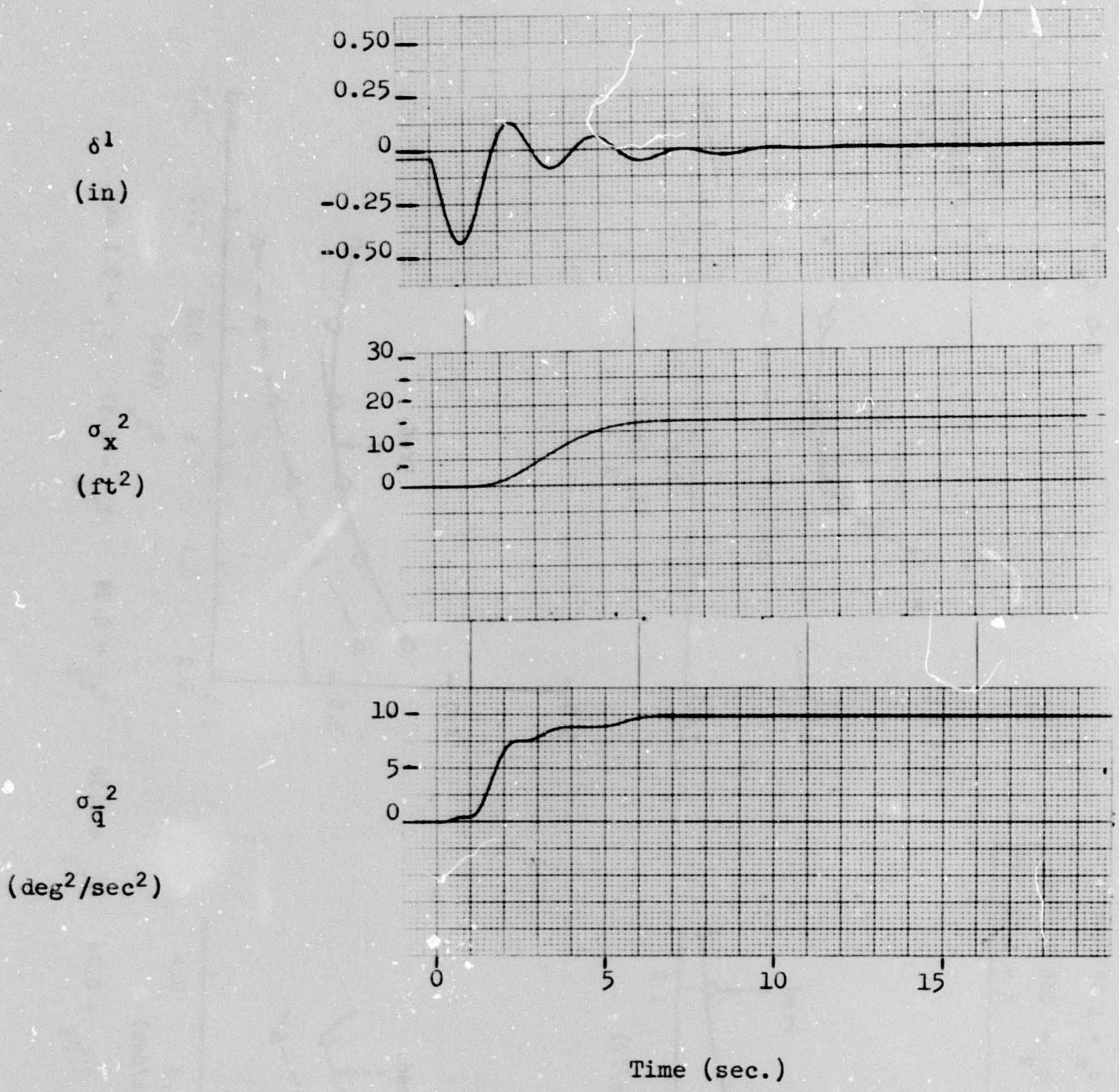


Figure A-2. Transient Analog Responses (Continued)

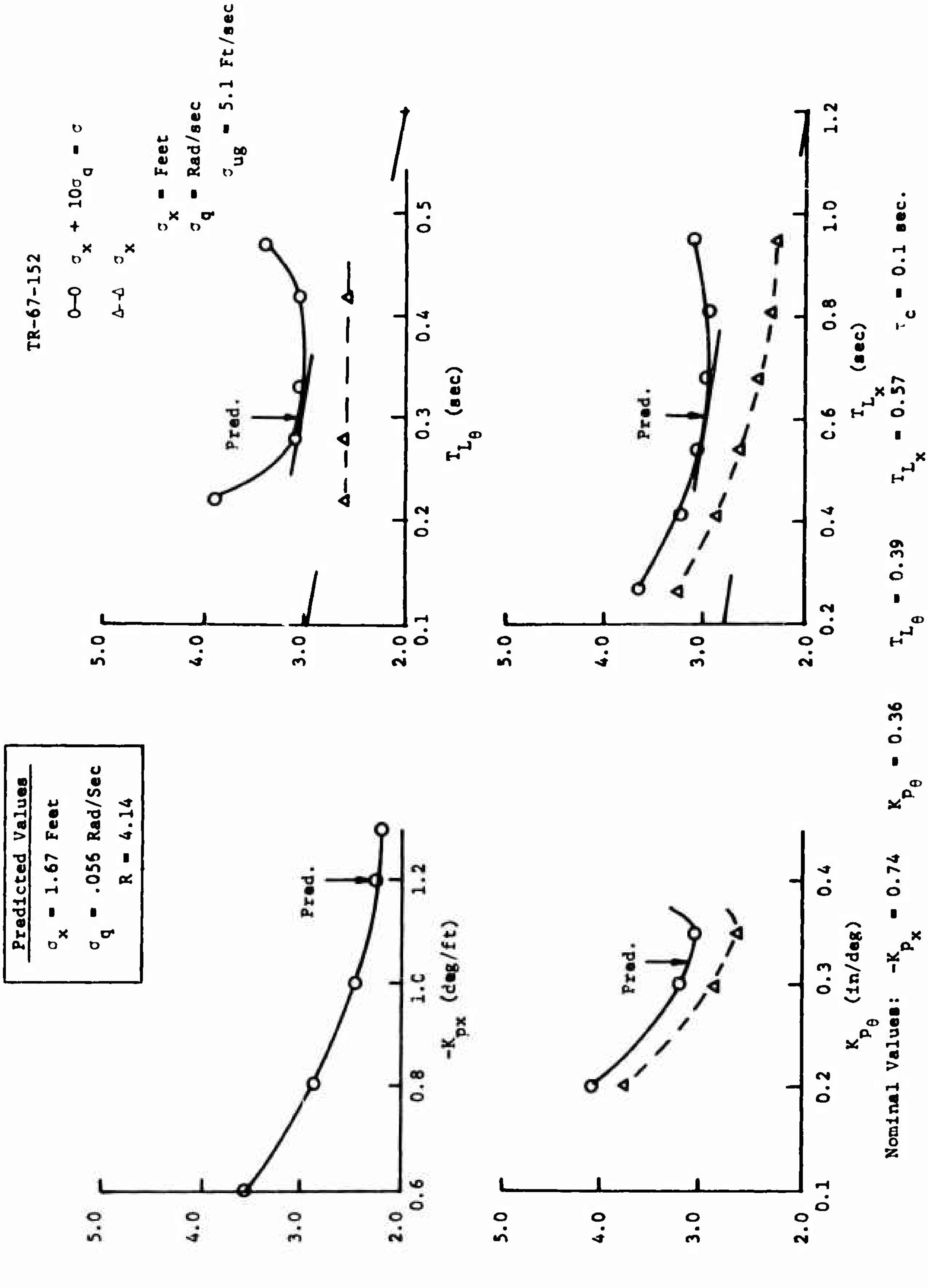


Figure A-3. PH3 With Actuator Lag of 0.1

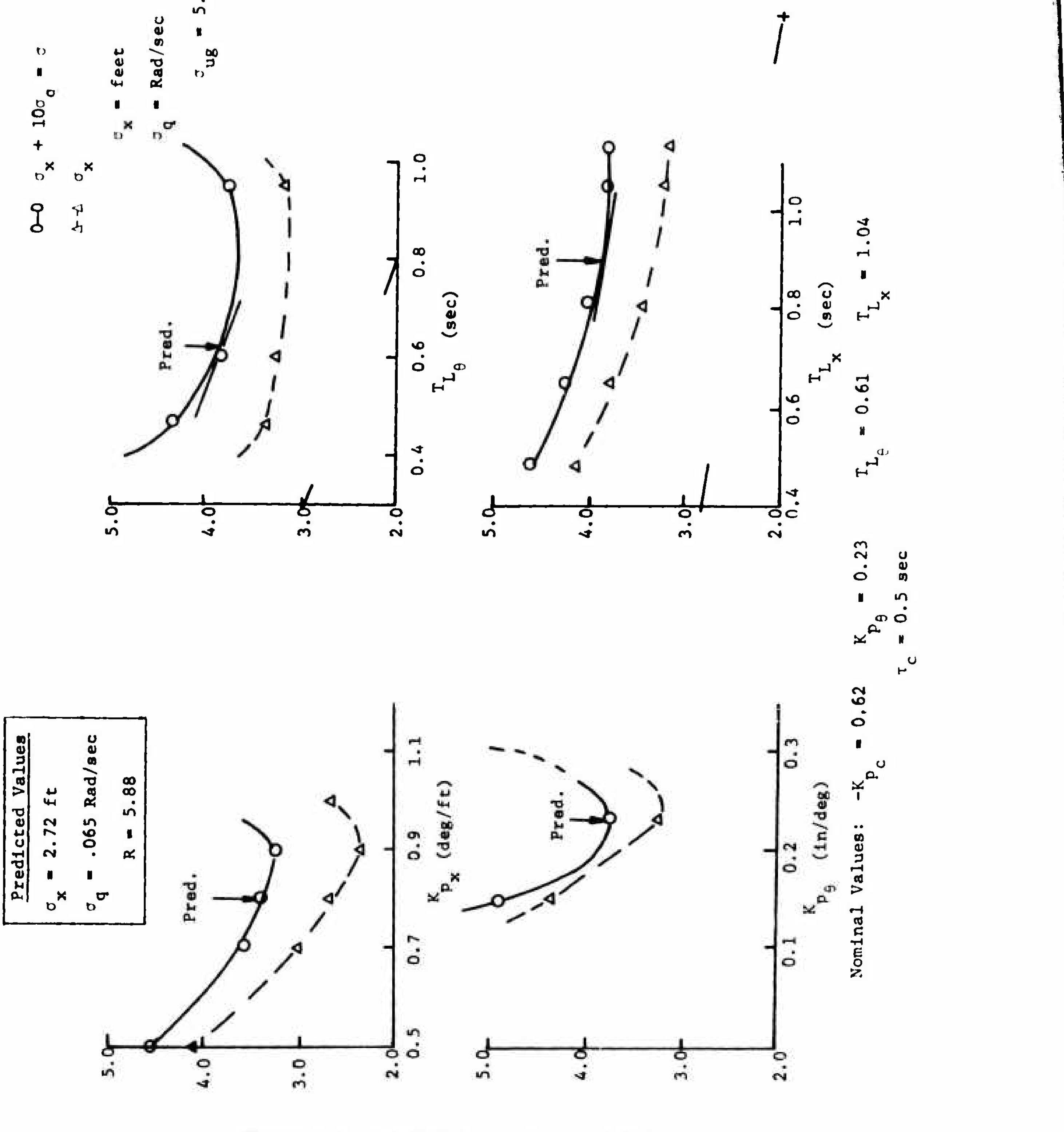


Figure A-4. PH3 With Actuator Lag of 0.5

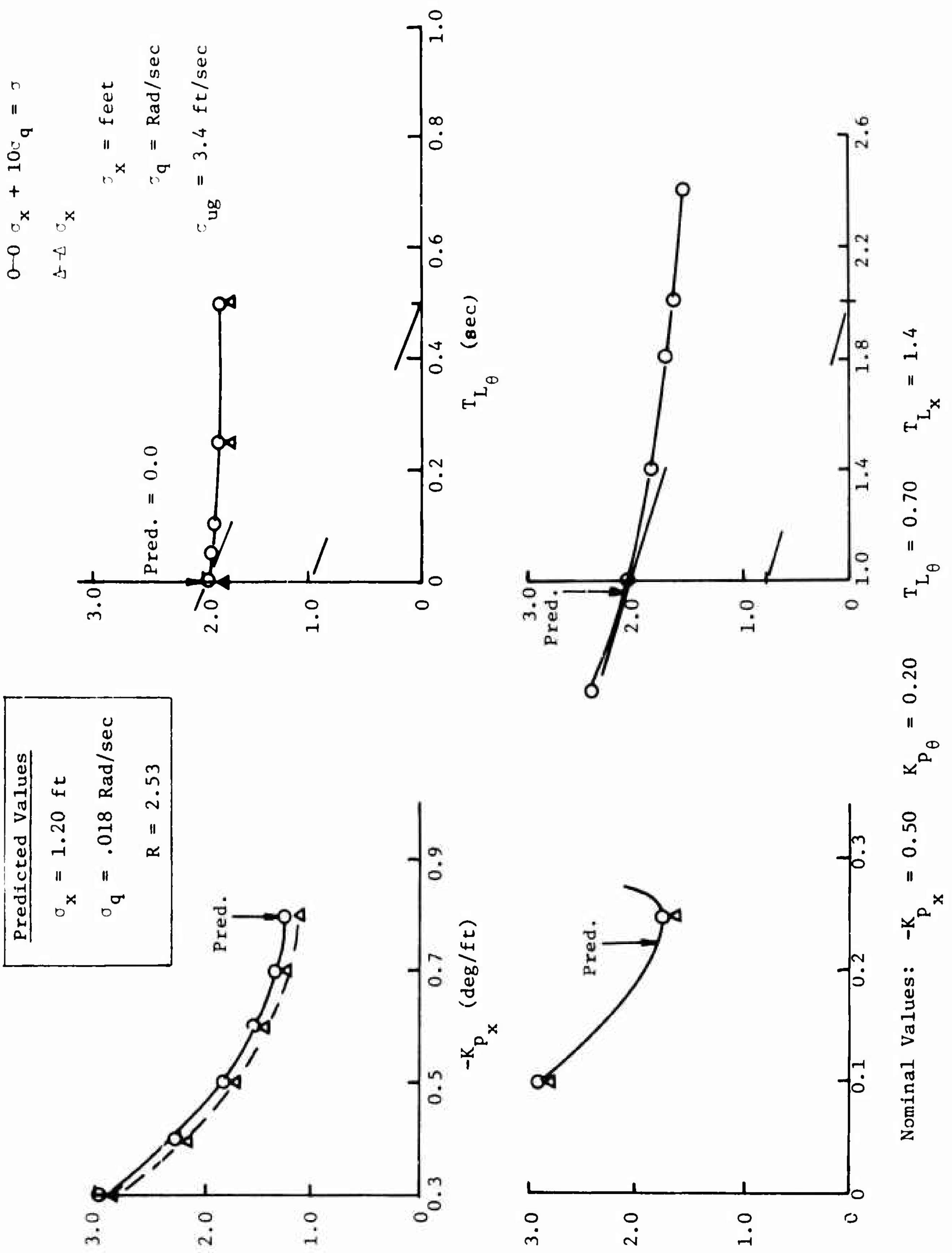
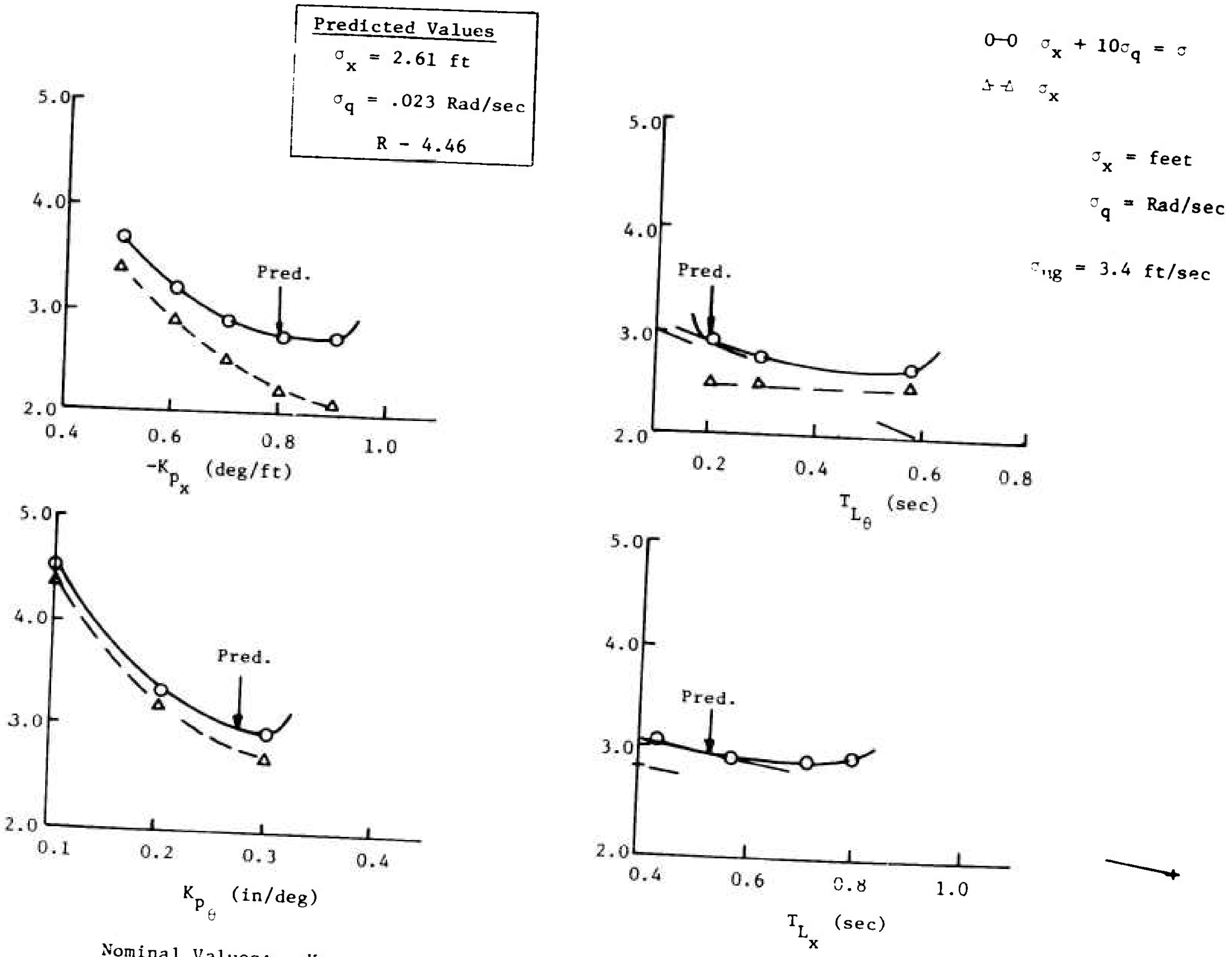


Figure A-5. McCormick Case 113



Nominal Values: $-K_{p_x} = 0.70$ $K_{p_\theta} = 0.35$ $T_{L_\theta} = 0.20$ $T_{L_x} = 0.71$

Figure A-6. McCormick Case 126

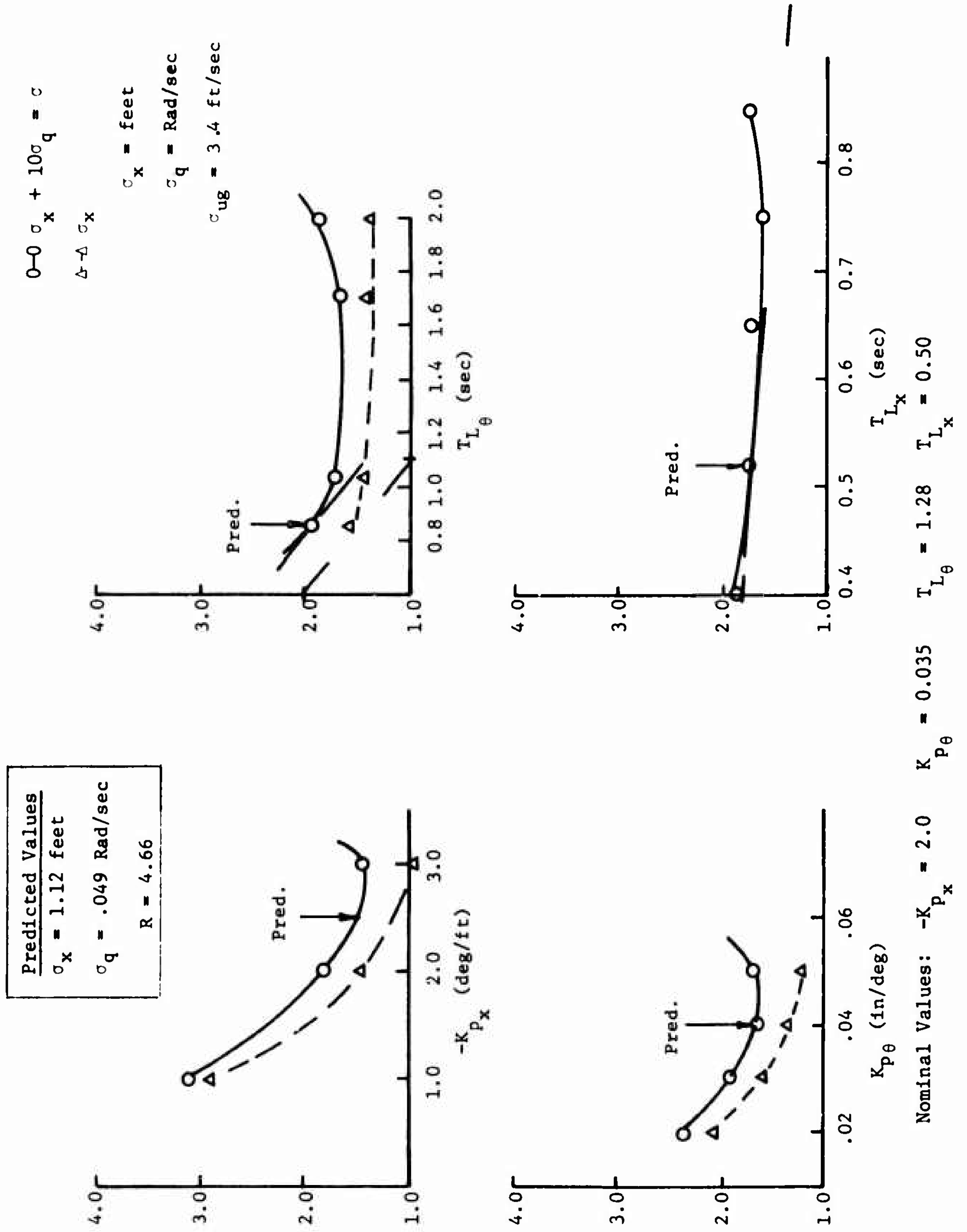
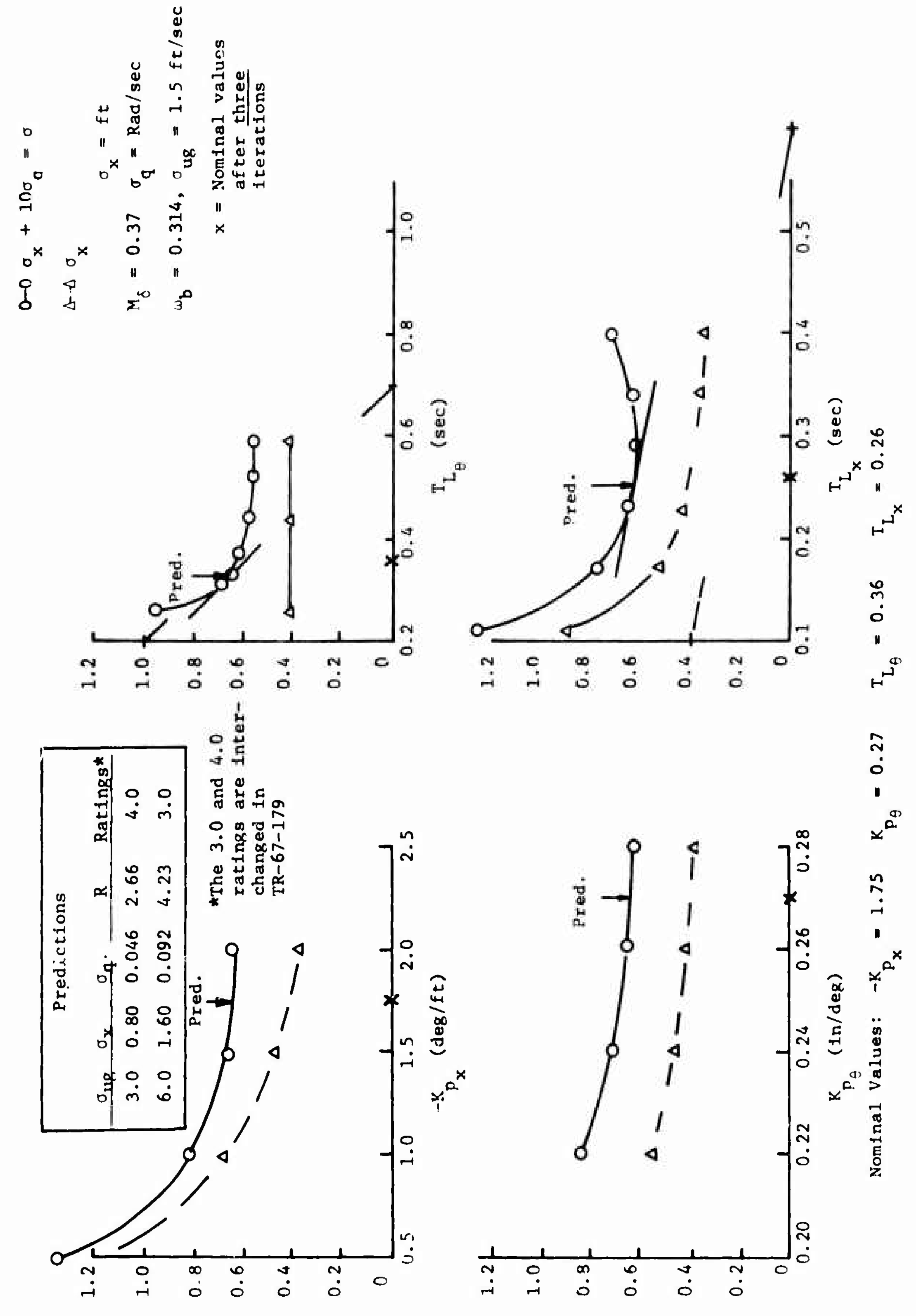


Figure A-7. McCormick Case 124

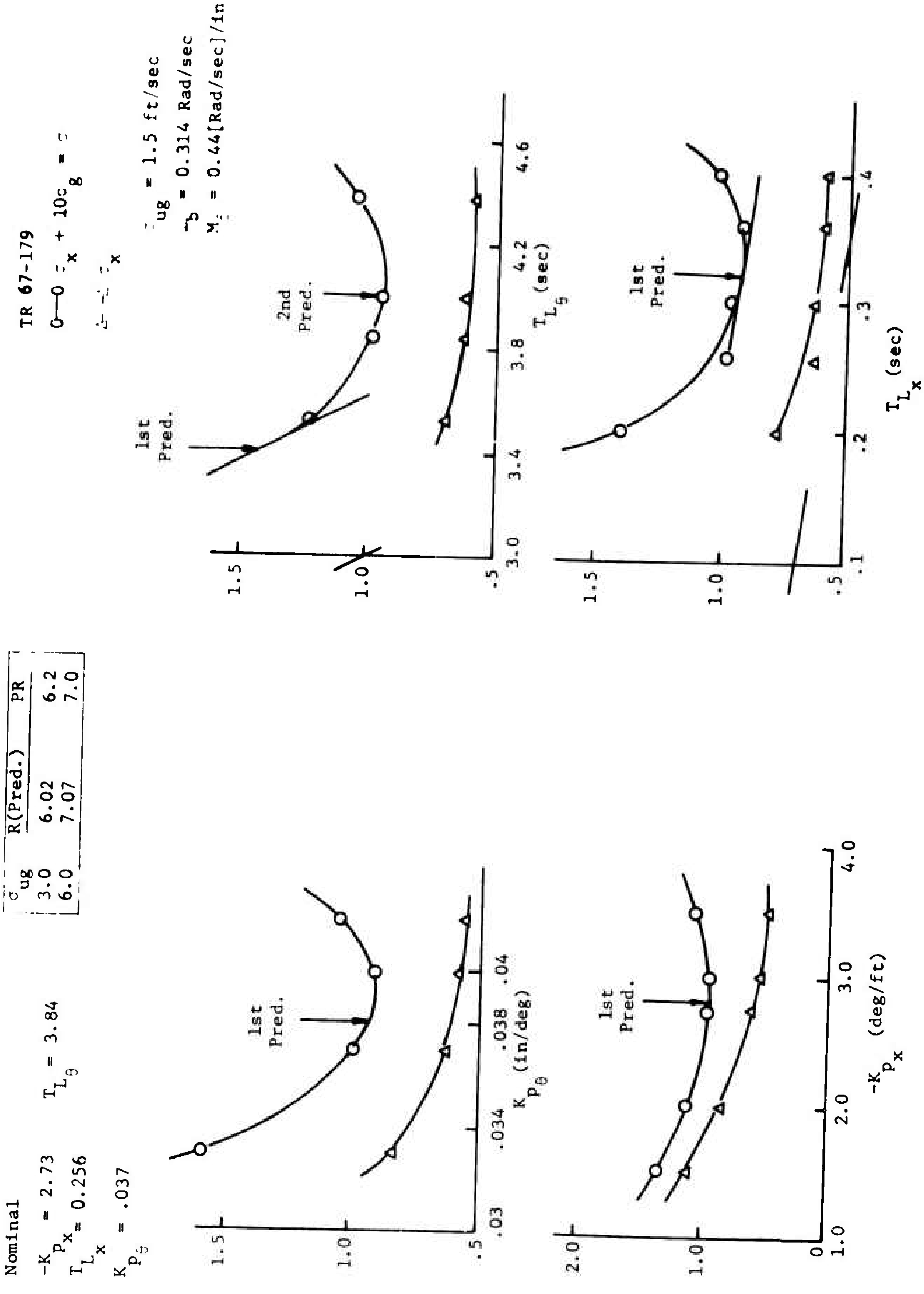


σ_{ug}	σ_x	σ_q	R	Ratings*
3.0	0.80	0.046	2.66	4.0
6.0	1.60	0.092	4.23	3.0

*The 3.0 and 4.0 ratings are interchanged in TR-67-179

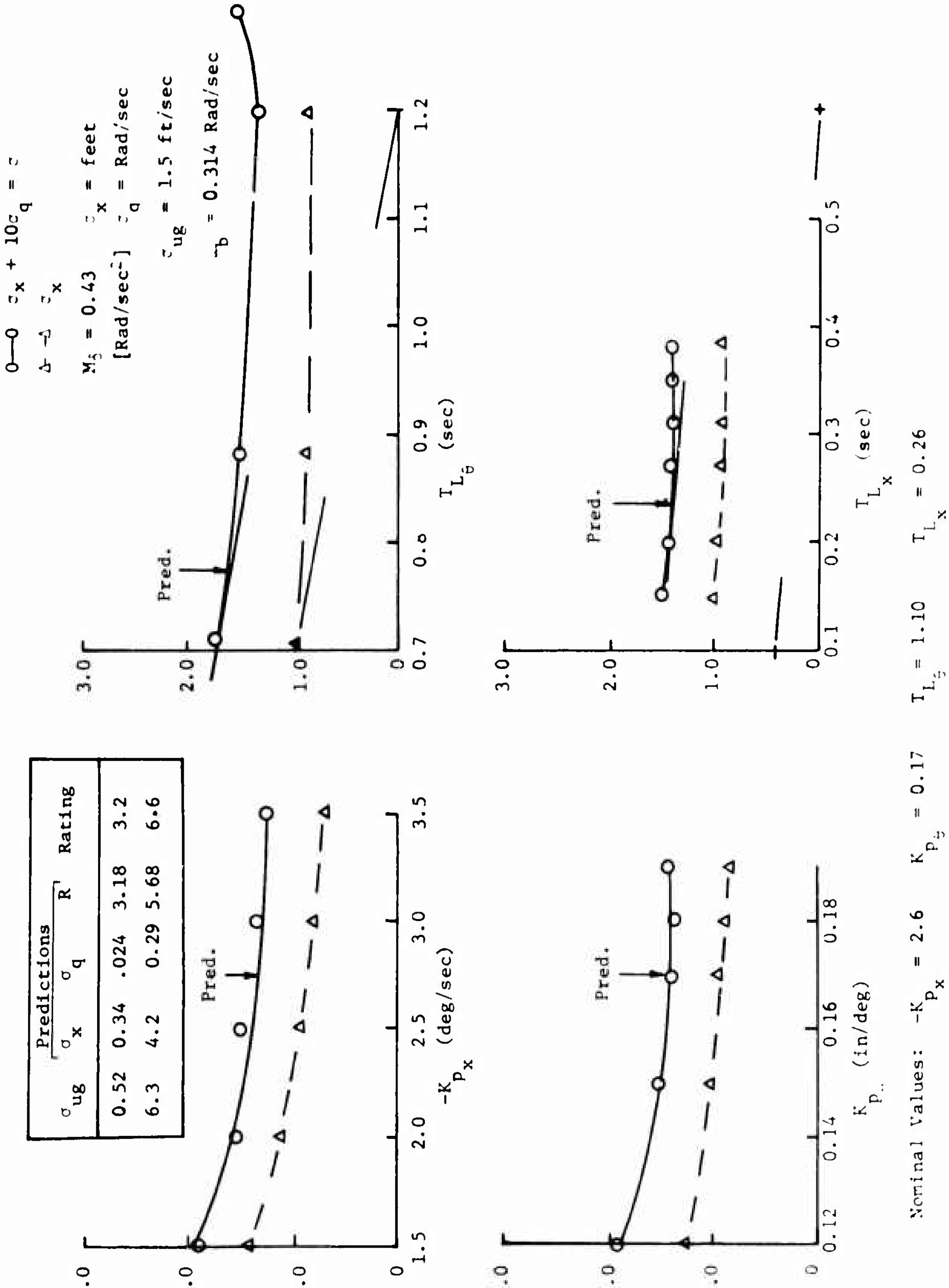
Nominal Values: $-K_{p_x}$ = 1.75 K_{p_θ} = 0.27 T_{L_θ} = 0.36 T_{L_x} = 0.26

Figure A-8. Breul Case 8



σ$_{ug}$	R(Pred.)	PR
3.0	6.02	6.2
6.0	7.07	7.0

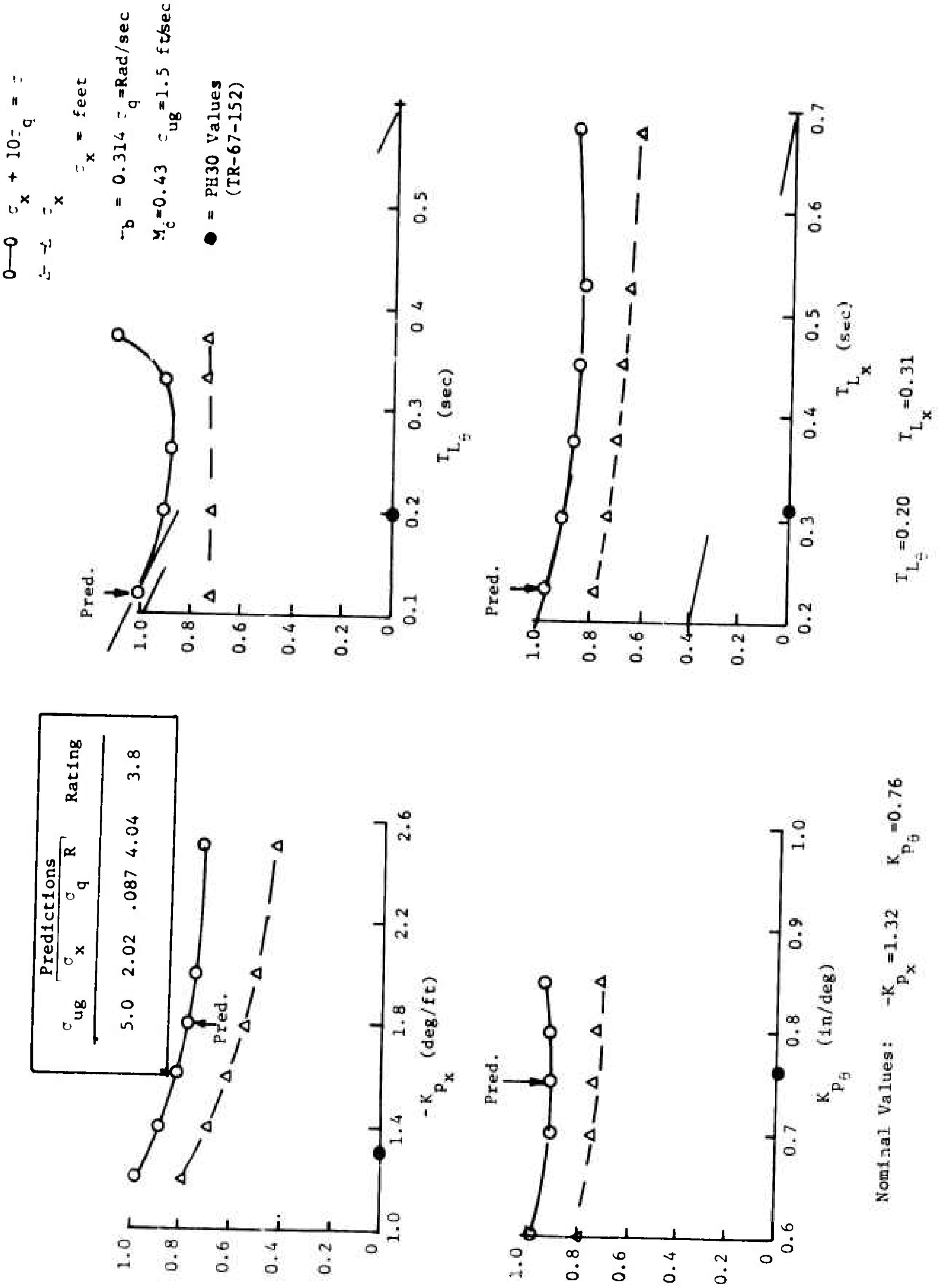
Figure A-9. Breul Case 4



σ_{ug}	Predictions σ_x	σ_q	R	Rating
0.52	0.34	.024	3.18	3.2
6.3	4.2	0.29	5.68	6.6

Nominal Values: $-K_{p_x} = 2.6$ $K_{p_\theta} = 0.17$ $T_{L_\theta} = 1.10$ $T_{L_x} = 0.26$

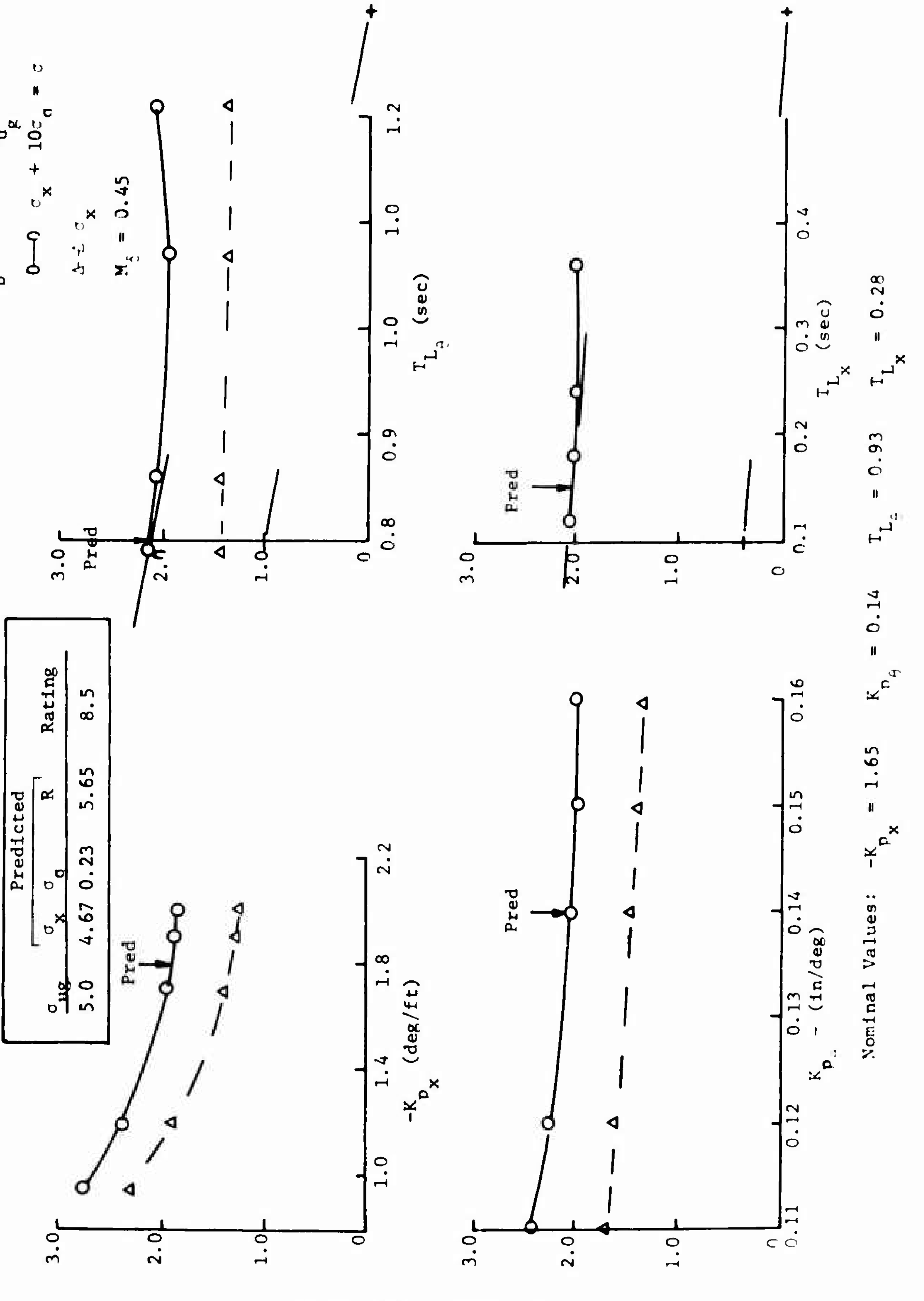
Figure A-10. Seckel Case 43



Predictions				
σ_{ug}	σ_x	σ_q	R	Rating
5.0	2.02	.087	4.04	3.8

Nominal Values: $-K_{p_x}=1.32$ $K_{p_\theta}=0.76$ $T_{L_\theta}=0.20$ $T_{L_x}=0.31$

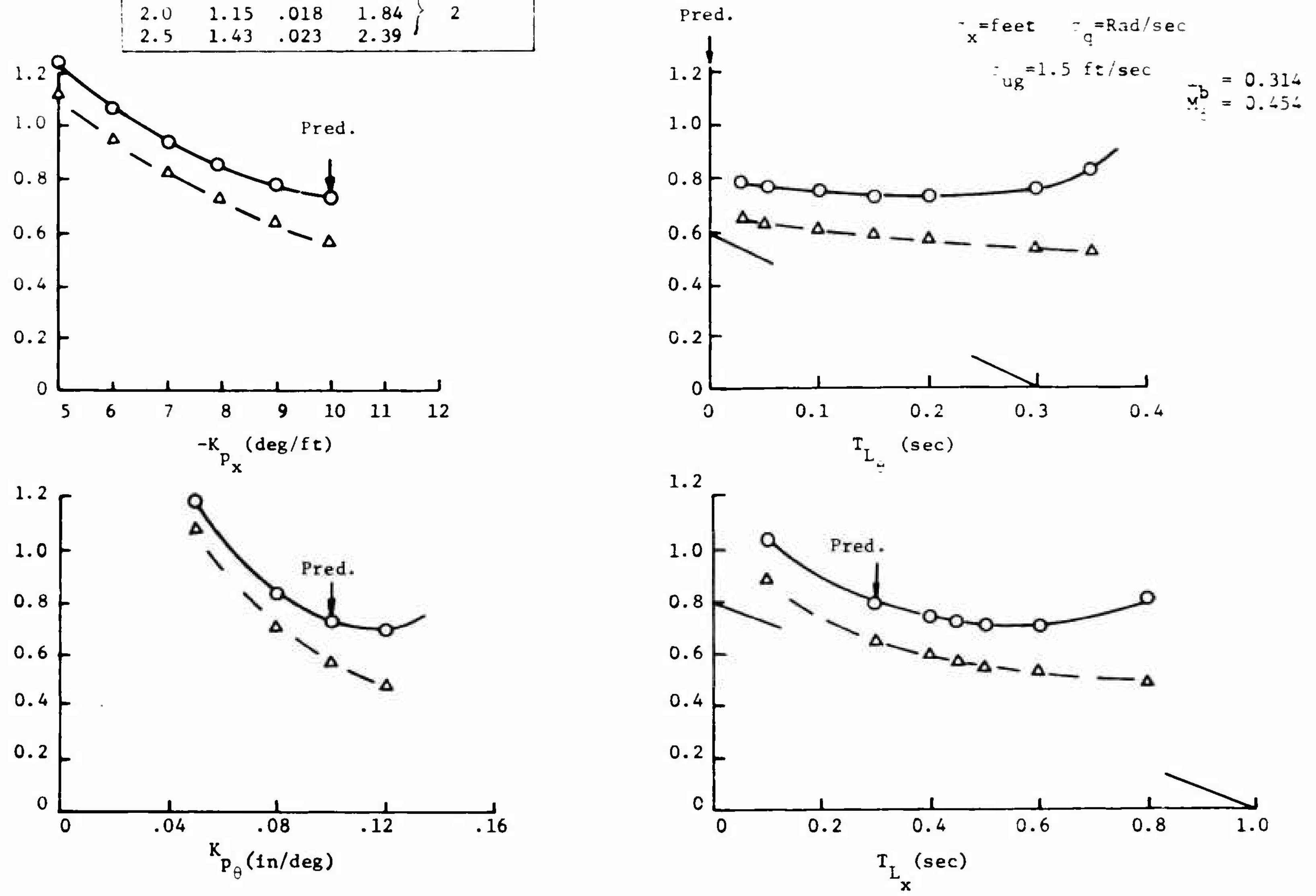
Figure A-11. A'Harrah Case 47



Nominal Values: $-K_{p_x} = 1.65$ $K_{p_q} = 0.14$ $T_{L_q} = 0.93$ $T_{L_x} = 0.28$

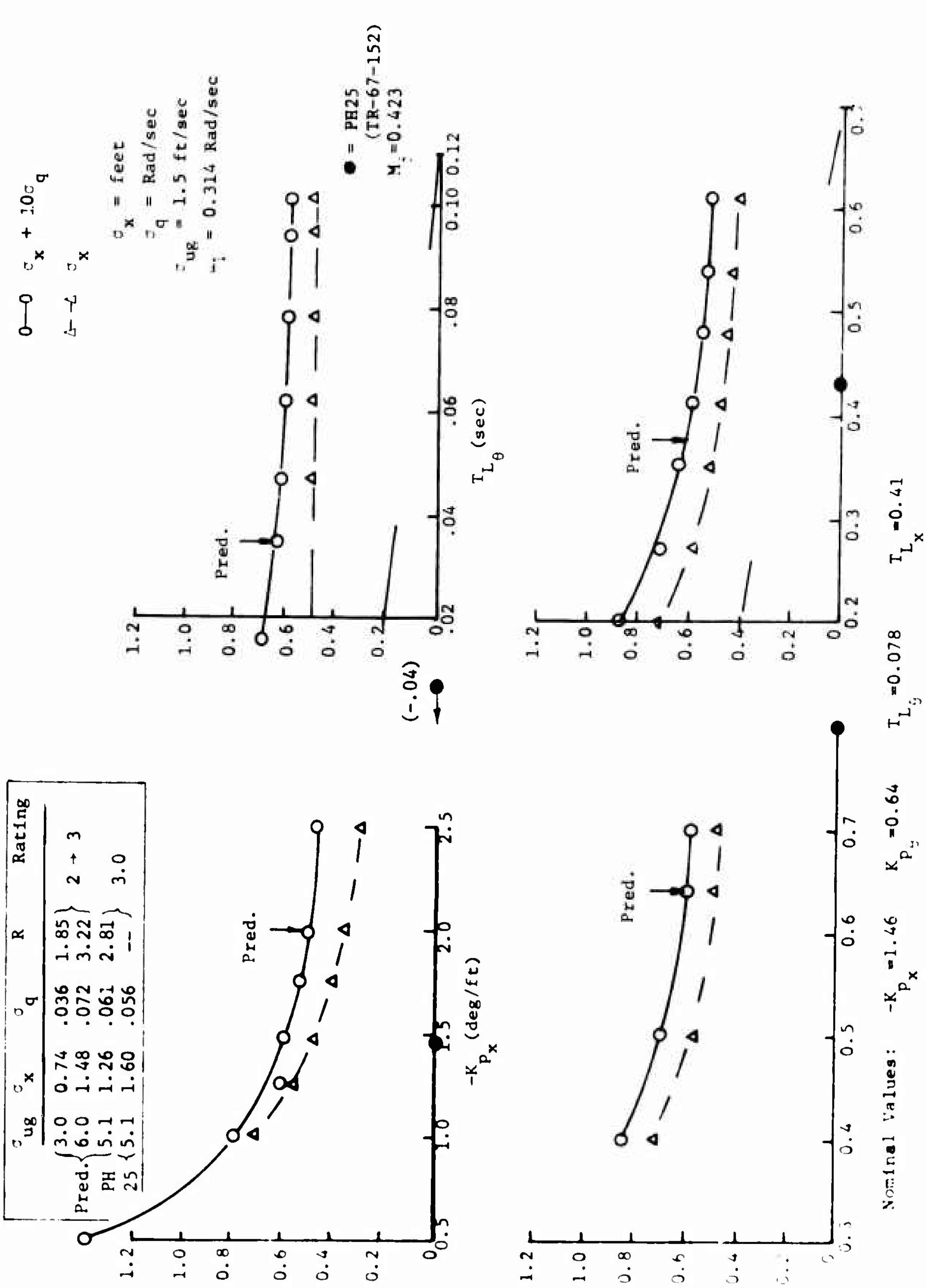
Figure A-12. A'Harrah Case 55

σ_{ug}	σ_x	σ_q	R	Rating
1.5	.86	.014	1.55	2
2.0	1.15	.018	1.84	
2.5	1.43	.023	2.39	



Nominal Values: $-K_{p_x}=10$ $K_{p_\theta}=0.10$ $T_{L_\theta}=0.20$ $T_{L_x}=0.45$

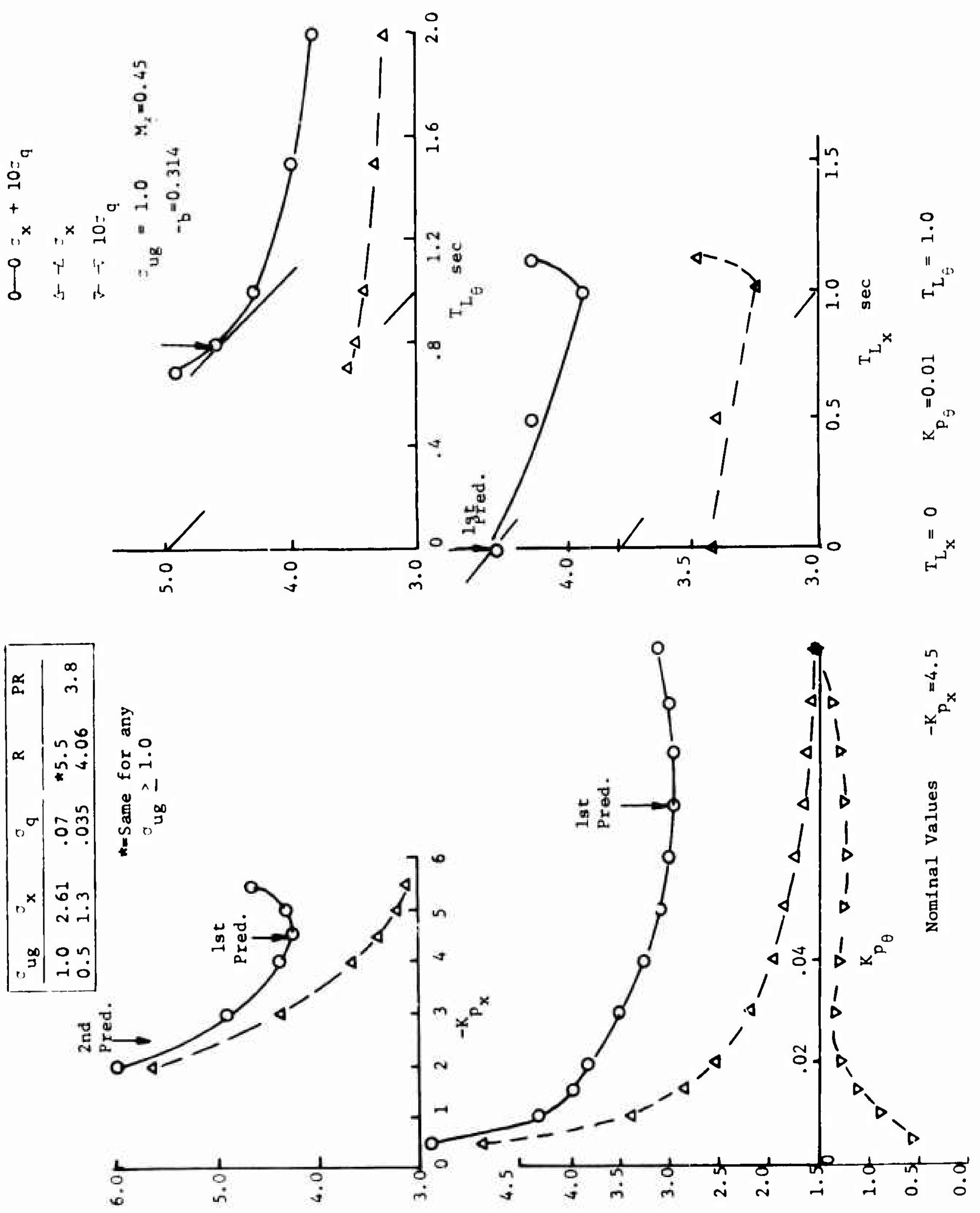
Figure A-13. Madden Data No. 1



σ_{ug}	σ_x	σ_q	R	Rating
Pred. {3.0	0.74	.036	1.85 }	2 → 3
6.0	1.48	.072	3.22 }	
PH {5.1	1.26	.061	2.81 }	3.0
25 {5.1	1.60	.056	-- }	

Nominal Values: $-K_{p_x}$=1.46 K_{p_θ}=0.64 T_{L_θ}=0.078 T_{L_x}=0.41

Figure A-14. Shaw Data No. 2



σ_{ug}	σ_x	σ_q	R	PR
1.0	2.61	.07	*5.5	3.8
0.5	1.3	.035	4.06	

Figure A-15. A'Harrah Data No. 11

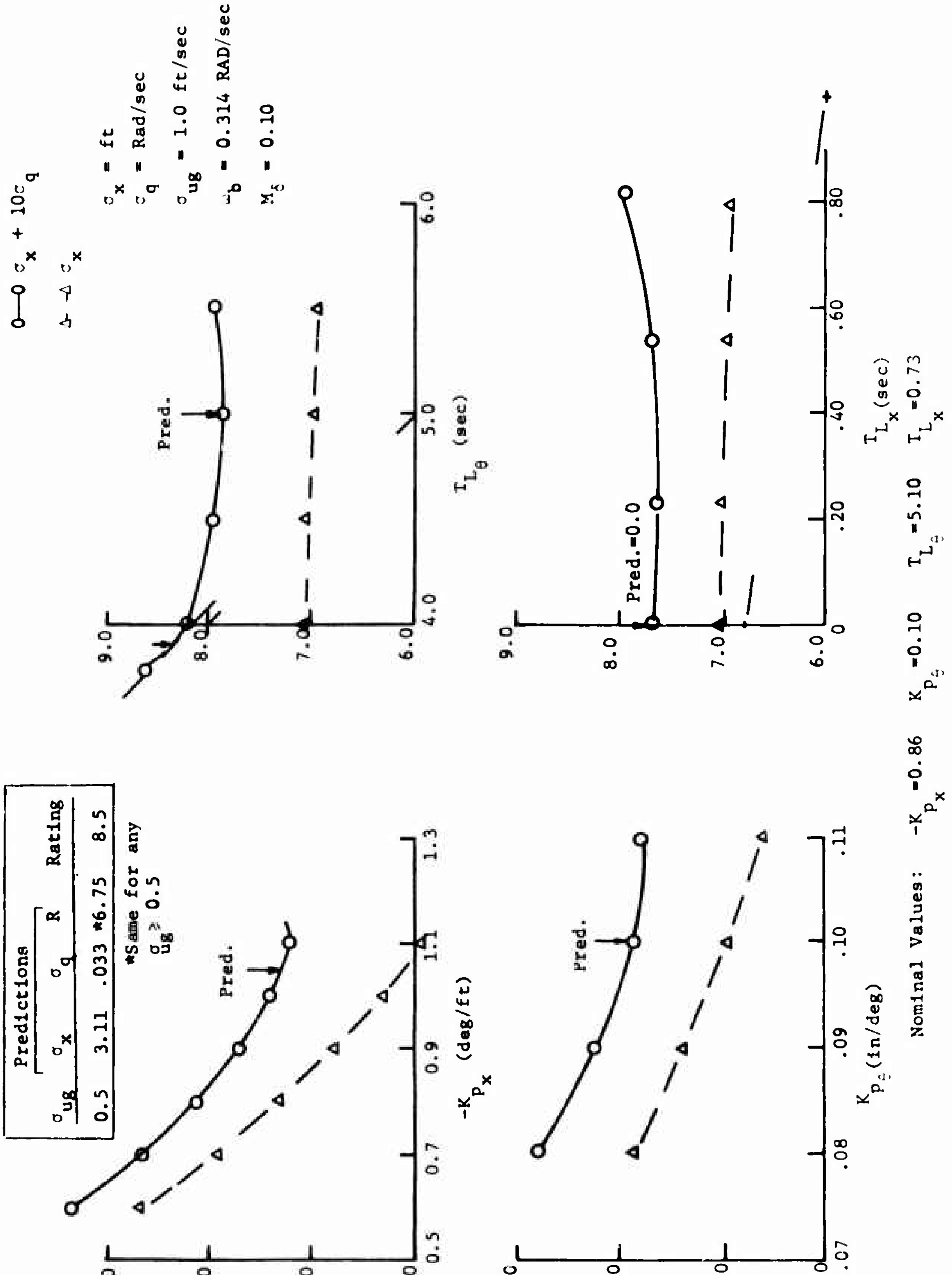
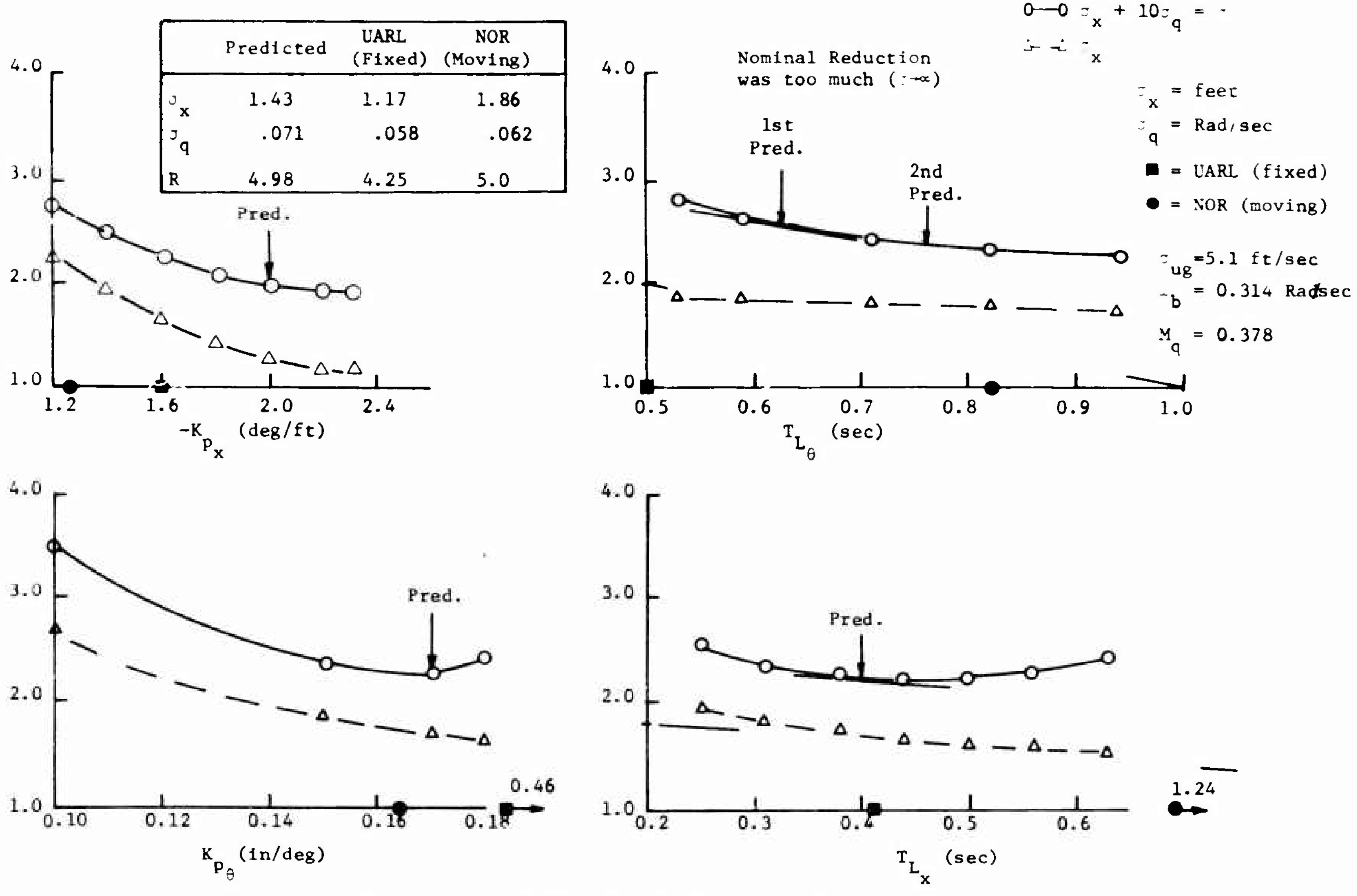


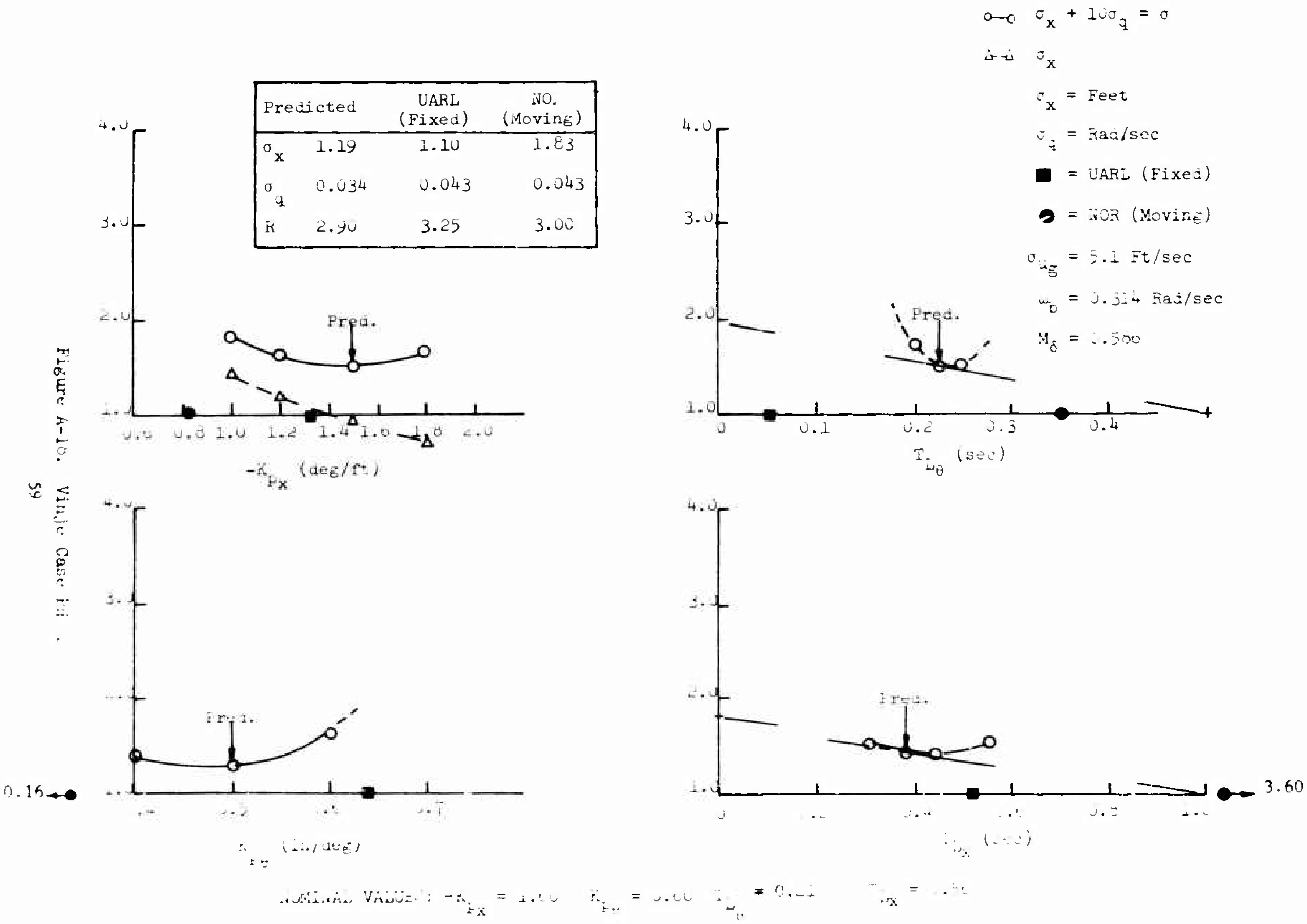
Figure A-16. A'Harrah Data No. 15



	Predicted	UARL (Fixed)	NOR (Moving)
σ_x	1.43	1.17	1.86
σ_q	.071	.058	.062
R	4.98	4.25	5.0

Nominal Values: $-K_{p_x}$ =1.60 K_{p_θ} = 0.17 T_{L_θ} = 1.06 T_{L_x} = 0.41

Figure A-17. Vinje Case PH10



Predicted		UARL (Fixed)	NO. (Moving)
σ_x	1.19	1.10	1.83
σ_q	0.034	0.043	0.043
R	2.90	3.25	3.00

Figure A-18. Vinje Case PH

APPENDIX B

PROPOSED SUPPLEMENT TO "HOVER AND LOW SPEED REQUIREMENTS"(REFERENCE 1)

The following paragraphs would be added (some in definition section):

3.2.2.3 Other Systems: If the vehicle-control system dynamics are such that the above requirements in 3.2.2.1 or 3.2.2.2 are not applicable, then the following expressions will be used to predict pilot rating for the longitudinal or lateral axes during pilot-controlled hover:

$$R = R_1 + R_2 + R_3 + 1.0$$

where: $R_1 = \left(\frac{\sigma - \sigma_m}{\sigma_m}\right)$, $\sigma_m = 0.80$

$$\sigma = \sigma_x + 10\,\sigma_q$$

$$0 \leq R_1 \leq 2.50$$

and: σ_x = standard deviation of x displacement in feet (or σ_y as appropriate).

σ_q = standard deviation of pitch rate in rad/sec, (or σ_p as appropriate).

Also, $R_2 = 2.5\ T_{L_\theta}$

$R_2 \leq 3.25$

T_{L_θ} = Pilot lead time constant in pitch (or roll)

$$0 \leq T_{L_\theta} \leq 5.0$$

and $R_3 = 1.0\ (T_{L_x})$

$R_3 \leq 1.20$

T_{L_x} = Pilot lead time constant in x displacement (or y)

$$0 \leq T_{L_x} \leq 5.0$$

Preceding page blank

3.2.2.3.a. Pilot Rating Requirements: The resulting "pilot" rating predictions must meet the following requirements for longitudinal or lateral hovering task (whichever is in question). With the pilot attempting to hold a fixed position over the ground, it shall be possible to achieve:

Level 1.	$R \le 3.5$
Level 2.	$3.5 < R \le 5.5$
Level 3.	$5.5 < R \le 6.5$

3.2.2.3.b. Environment: The pilot rating predictions shall be made under gust (u_g or v_g) disturbances described by a power spectral density of:

$$\Phi_{gg}(\omega) = \frac{2\omega_b \sigma_g^2}{\omega^2 + \omega_b^2}, \quad \sigma_g^2 = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Phi_{gg}(\omega)\, d\omega$$

where ω = angular frequency - rad/sec

$\omega_b = 0.314$

$\sigma_g = \sigma_{u_g} = \sigma_{v_g} = 5$ ft/sec for gust intensity standard deviation and both gusts are zero mean, Gaussian random variables.

3.2.2.3.c. Alternates: The prediction expression in 3.2.2.3 contains a high bandwidth loop (about 3 rad/sec) lead term designated T_{L_θ} and a low bandwidth (1 rad/sec) loop lead term T_{L_x} to cover most hovering tasks where attitude changes are required to produce translation. If the system under question is different then any or all of the following apply:

- no more than two loops (and two lead term generations) may be closed by the pilot in a given axis (longitudinal or lateral).

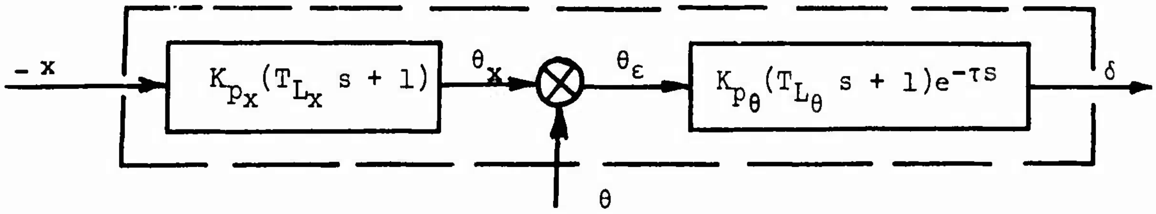
- expression R_2 shall be used for each loop where lead is generated and the bandwidth of that loop is greater than 1.5 rad/sec.

- if direct control of position error is provided, then only a single pilot lead term of the R_2 form will be used together with single loop control, and pilot gain.

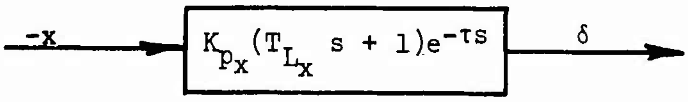
- in all cases the R_1 term will be included along with the unity term.

3.2.2.3.d. Pilot Gains and Time Constant Variations: In all of the above cases the pilot gains (K_{p_θ}, K_{p_x}) may be varied to produce the smallest R. This shall be accomplished by first ignoring the upper limit on the R_1 term and finding values for the pilot parameters that minimize R. Next, the limit on the R_1 term shall be considered in the final computation of R. In addition, system stability (e.g., σ = finite) must be maintained with gain and lead time constant variations of $\pm 20\%$ of the nominal (minimal R) values varied in the worst combination.

3.2.2.3.e. Assumed Pilot Forms:



or:



where: τ = 0.44 seconds, and

$e^{-\tau s}$ may be approximated by $\frac{-(s-2/\tau)}{(s+2/\tau)}$

The second form is for direct translation control (Par. 3.2.2.3.c.).

The total addition presented above may seem long, but it should be remembered that many of the definitions belong in Section 6, and in an appropriate 3.7 section on "Atmospheric disturbances" similar to MIL-F-008785A. Since the above also really covers both rate and attitude systems as well, it could replace all of Paragraph 3.2.2. On the other hand, it could serve as presented here to cover cases not presently covered in the requirements.

The body of this report serves as the main substantiation for the proposed requirement. However, it should also be stated that the limits on T_L's are based on observed data (Reference 9), and the required gain margins are substantiated further in Reference 18.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Air Force Flight Dynamics Laboratory (FDCC)
Wright-Patterson AFB, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP
N/A

3. REPORT TITLE
A NEW APPROACH TO THE SPECIFICATION AND EVALUATION OF FLYING QUALITIES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report

5. AUTHOR(S) *(Last name, first name, initial)*
Ronald O. Anderson

6. REPORT DATE
November 1969

7a. TOTAL NO. OF PAGES
63

7b. NO. OF REFS
22

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 8219

c. Task: 821909

d. Work Unit 004

9a. ORIGINATOR'S REPORT NUMBER(S)
AFFDL-TR-69-120

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
None

10. AVAILABILITY/LIMITATION NOTICES
Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES
None

12. SPONSORING MILITARY ACTIVITY
Air Force Flight Dynamics Laboratory
Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A study of the correlation of pilot model parameters and closed-loop performance with pilot opinion of VTOL hover dynamics was conducted. The encouraging results suggested a pilot-vehicle analysis method of predicting pilot model parameters, closed-loop pilot-vehicle performance with gust inputs, and pilot opinion ratings for a wide range of vehicle dynamics. This approach was, in turn, used to predict ratings for comparison with fixed base, moving base, and flight test results for VFR conditions. Again the results were promising, and a new method of specifying hover dynamics followed naturally. The new pilot-vehicle analysis concept, called the minimum pilot rating method, is discussed in terms of applications to other tasks, flying qualities specification, and control system design.

DD FORM 1 JAN 64 **1473**

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flying Qualities						
Human Response						
Manual Control						
Pilot Opinion Rating						
Pilot-vehicle Analysis						
Hover Dynamics						
V TOL Aircraft						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.