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**Scientific and Technical
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SUMMARY

A full-factorial in-simulator experiment of a single-axis, multiloop, compensatory-pitch tracking task is described. The experiment was conducted to provide data to validate extensions to an analytic, closed-loop model of a real-time digital simulation facility. The results of the experiment encompassing various simulation fidelity factors, such as visual delay, digital integration algorithms, computer iteration rates, control-loading bandwidths and proprioceptive cues, and g-seat kinesthetic cues, are compared with predictions obtained from the analytic model incorporating an optimal control model of the human pilot.

The in-simulator results demonstrate more sensitivity to the g-seat and to the control-loader-conditions than were predicted by the model. However, the model predictions are generally upheld, although the predicted magnitudes of the states and of the error terms are sometimes off considerably. Of particular concern is the large sensitivity difference for one control-loader condition, as well as the model/in-simulator mismatch in the magnitude of the plant states when the other states match.

Also of interest in the experimental results is the tendency for detectable differences to occur only under the more difficult task conditions. This finding concurs with current thinking on trade-offs between simulation fidelity and cost being based on the specific flight task being simulated.

INTRODUCTION

Both the military and the civilian segments of aviation are placing an increasing reliance on flight simulators for pilot training and proficiency maintenance. This fact, combined with the increasing sophistication and the associated costs of simulation devices available, has placed increased emphasis on the numerous trade-offs between simulation fidelity and costs. In determining the simulation configuration required to meet certain goals, the designer must consider the need for particular cueing devices as well as the requisite level of fidelity to be provided by that device. For existing configurations, the simulation user should have some knowledge of the constraints placed upon the man and machine system performance (including trade-offs of performance and workload) by that level of simulation fidelity.

For these reasons, NASA Langley Research Center (LaRC) has sponsored development of an analytic closed-loop model of the Langley Real-Time Simulation System (refs. 1 and 2). This simulation facility model combines a multiaxis model for the human pilot (the optimal control model of refs. 3 to 5) with detailed models of the components of a simulator. The simulator models are flexible and allow the representation of all of the various LaRC simulators. These models are detailed enough to include the effects of discretization of the mathematical model of the simulated aircraft, the effects of digital computer iteration rate, and the effects of the interface conversion equipment (analog-to-digital convertors (ADC) and digital-to-analog convertors (DAC)). Models for the hardware components of the simulator, such as the visual-display systems, the control-loading (force-feel) system, and the motion cueing systems, are also included. These models provide representations of the important hardware system characteristics that affect the information being provided by these systems to the pilot (i.e., bandwidth, time delays, and so forth).

The total simulation facility model allows simulator design trade-offs to be quantitatively evaluated by the following process. An in-simulator experiment is conducted to obtain empirical data for the aircraft task of interest, using the simulation hardware equipment available for that task. The analytic model of the simulation facility is assembled to represent the subject simulator, and the parameters of the pilot model are chosen to produce pilot-vehicle performance that matches the data from the in-simulator experiment. In other words, the model of the simulation facility is "tuned" (i.e., the variable parameters are selected) about the local conditions (i.e., the specific simulation configuration) with the data from the in-simulator experiment. The analytic model can then be used to analyze both hardware and software design increments about these local conditions by changing the hardware and software representations of the simulator. The ensuing effects of these changes on task performance then provide the quantitative data for the evaluation of trade-offs between fidelity and cost.

Along with the development of the facility model, extensive validation efforts have been under way. Validation of the model involves the identification of the parameters of the subsystem models (both hardware and software) excluding the human pilot. Then, a tuning process with in-simulator data is used to determine the parameters of the pilot. Successful validation is obtained if the model results, once tuned across all experimental conditions, fall within the pilot data scatter observed in the simulator experiment for each experimental condition.

After reviewing the history of the previous validation efforts, the current efforts to validate some of the recent extensions of the closed-loop facility model are presented. Unlike the previous validation efforts, the current efforts involve use of the facility model in an untuned mode. That is, the model is used to predict the in-simulator results. The simulator experiment reported herein was then conducted. The process of tuning the facility model to these data has not been attempted at this time.

After the brief review of the previous validation efforts, this paper describes the facility configuration for the current effort, reviews the untuned-model predictions, and presents the in-simulator experimental results. Comparisons of the predicted results with the experimental results are then made. Detailed descriptions of the facility model are found in reference 2.

VALIDATION HISTORY

References 6 and 7 report the first in-simulator experiment conducted to provide data for tuning and validating the facility model. The experiment was conducted to examine the effects of sample frequency, integration scheme, visual servo dynamics, and control-loader implementation on a single-axis, multiloop, compensatory-pitch tracking task. The results are presented in figure 1 and tables I and II. (The simulator configurations are also used in the present study and are discussed in some detail later.) The error scores from the model for the various conditions were averaged over the various simulator configurations to "mimic" the statistical presentation of the experimental data; thus, the presentation of standard deviations in figure 1 rather than single points for the model results is possible. Although the effects of the variations in the simulator fidelity factors were known, at least intuitively, prior to the experiment, empirical verification was still obtained. The relative effects of each fidelity factor, all of which were related to the digital nature of the simulator dynamics, were also of interest, with sample rate and integration scheme having the largest effects. More significantly, the range of simulator configurations and their effects yielded an effective test for the facility model.

This validation effort was deemed successful. The model only provided the limitations imposed by the dynamics of the software and hardware components of the simulator. The perceptual issues in visual, force-feel, and motion cue generation were not considered. Recent extensions of the model provided for not only the dynamics of the cue generation equipment, but also for the perceptual considerations, including models for human operator sensory dynamics. These extensions have resulted in a multicue version of the facility model which allows representation of the human operator's visual, vestibular, proprioceptive, and tactile sensory systems (ref. 8).

The incorporation of these systems into the model could allow the informational cues available from such simulator cueing devices as motion platforms, g-seats, g-suits, helmet loaders, and control loaders (stick position, rate, and force) to be added to the observation set of the human operator model. Unfortunately, as discussed in reference 8, few of the limitations associated with the perceptions of these cues are very well known quantitatively, and so at the present time, it is assumed that these cueing devices provide the desired information directly to the observation set.

The validation of the multicue version of the facility model will continue as understanding of human perceptual processing grows. This paper presents the results of a full-factorial in-simulator experiment conducted on a single-axis, multiloop, compensatory-pitch tracking task to provide data to begin validation of some of the aforementioned extensions of the closed-loop facility model. The cueing extensions to the model were to be tested by in-simulator variations in control-loading and g-seat operations. Motion cueing was not tested, as the simulator used in this experiment was a fixed-base simulator.

SIMULATION FACILITY DESCRIPTION

The simulation configurations used to collect the validation data were provided through various implementations of the Langley Differential Manuevering Simulator (DMS) (ref. 9). The DMS (fig. 2) is a wide-angle, visual simulator which allows one-on-one aircraft interactions. However, in order to provide the desired range in visual time delay, a head-up display (HUD) with a wide field of view (25° × 35°) was used to present a target image and horizon line (fig. 3) to the pilot in a single sphere. The fixed-base cockpit is equipped with a programmable, hydraulically actuated control-loader system and a g-seat to provide some motion-induced force cues to the pilot. The aircraft dynamics programmed on the Control Data CYBER 175 host digital computer for this particular experiment represent the same linearized version of the F-8 airplane used in reference 6.

Two different implementations (the "best" and "worst" conditions of refs. 6 to 8) of the DMS hardware and software systems were used in this experiment. The "best" condition consisted of the following fidelity elements:

1. A visual time delay of 12 msec, the minimum achievable with the DMS HUD symbology

2. Solution of the equations of motion by using a second-order, one-pass Adams-Bashforth (AB2) integration algorithm (ref. 2)

3. A computer iteration rate of 32 per second (yielding an integration real-time step size of 31.25 msec)

4. An analog implementation of the cockpit control-loader-system loop closures for stiffness and damping that eliminates discretization effects on control-loader bandwidths (ref. 10)

The "worst" condition consisted of the following fidelity elements:

1. A visual time delay of 68 msec, obtained by adding a 25 rad/sec second-order filter with a 56 msec steady-state time delay to the HUD drives (representative of the normal DMS projection-servo response characteristics)

2. Solution of the equations of motion by using Euler integration

3. A computer iteration rate of 16 per second (yielding an integration real-time step size of 62.50 msec)

4. The conventional digital force-feedback implementation of the control-loader system that induces control-loader bandwidth reductions (ref. 10)

The model extensions examined across these two simulator conditions were the provisions for acceleration sensing (which could represent a g-seat, a helmet loader, or platform motion; only the g-seat model was used in this study) and the control-loading informational effects (stick position, rate, and force information subject to the dynamics of the control-loading system). The acceleration-sensing provisions (hardware dynamics and cue informational content without consideration of sensory organs) were examined by use-nonuse of the g-seat provided in the DMS (ref. 11). The control-loading effects were examined across the following three force gradients: light (5 lb/in), medium (10 lb/in), and a fixed, immovable stick. The fixed stick was implemented so as to provide the same time lag characteristics as the medium-force stick; thus, the only difference between these two stick conditions would have been due to stick position and stick rate feedback through the test subject's arm. Elevator movement per stick force was the same for all three control-loading (force-feel) systems.

In summary, 12 different simulation configurations were evaluated. The factors were simulator condition (best and worst); control-loading system (light gradient, medium gradient, and fixed stick); and g-seat (on and off).

TASK DESCRIPTION

A single-axis, multiloop, compensatory-pitch tracking task was used for the experiment. A block diagram illustrating the closed-loop components involved in the task is presented in figure 4. A sum of 13 sine waves with a fixed set of amplitudes and frequencies but randomly chosen phases (selected at the beginning of each tracking run to be between ±180°) was used to drive the vertical degree of freedom of the target aircraft. The phases were randomly chosen so that the test subjects would not learn the movements of the target. Table III presents the amplitudes and frequencies in the sum of sine waves. For the experiment, the target and the pursuit aircraft were limited to the two vertical degrees of freedom only. Therefore, neither aircraft could roll, yaw, or change throttle controls (fixed target range). The control actions of the test subject produced changes in the pitch and vertical motions only. Both aircraft were trimmed for level flight at an altitude of 20 000 ft with a constant speed of 325 knots and at a range of 600 ft. The pursuit aircraft used a standard backup reticle for the tracking reference. In order to "track" the target, the pilot of the pursuit aircraft was required to keep the tail of the target in the center of the reticle.

The performance measures for model and in-simulator comparisons included the root-mean square (rms) of the vertical tracking error, the pitch angle, the normal acceleration, and the stick deflection. (The in-simulator experiment also included measures of the rms vertical tracking error rate and the rms altitude deviations from trim altitude; these measures were not available from the analytic model data that were provided in ref. 8.)

MODEL PREDICTIONS

In order to use the closed-loop model of the simulation facility to predict the results for each in-simulator experimental condition, three sets of parameters had to be specified. These sets consisted of those parameters associated with the simulator fidelity conditions ("best" or "worst"), those parameters of the human operator, and those parameters of the cueing extensions. The first two sets of parameters were obtained from references 2 and 7, respectively, although the results presented in the references are for slightly different target motions than those presented in table III. The third set of parameters was determined by experimental judgment and empirical model results, as reported in reference 8.

After correct specification of the parameters in the closed-loop facility model to represent the 12 experimental conditions, the values of the human operator model parameters determined in the study of reference 7 (see table IV) were used to predict in-simulator performance. These predictions from the "untuned" model (i.e., the informational aspects of control loading and g-seat conditions were untried) were presented in reference 8 and are presented here in figure 5. The results from the model and the in-simulator experiment, as reported in reference 7, are also presented in figure 5. These results were obtained with the g-seat off, without model representation of the control-loading informational contributions (stick position, rate, and force), and with a slightly different set of target motions. The model predictions give improved performance compared with the model results from reference 7 for both the best and the worst conditions. The improvement is much larger for the best case than for the worst case. The performance improvements are primarily due to the additional information provided to the human operator model by the control-loading extension, although some of the improvements may be attributed to the difference in target movement between the two studies. (The experimental data are used to quantify the effects of this change later.)

The lines connecting the model predictions in figure 5 are intended to link like g-seat conditions and are not intended to imply that the control-loading effect is continuous. Only three control-loading levels were examined. The figure illustrates the well-defined separation predicted for the best and worst conditions and shows only slight differences for the control-loading levels and the g-seat conditions. The fixed stick is predicted to give slightly higher values for all measures, particularly for the worst case condition, and the medium gradient stick is predicted to give slightly lower values. The g-seat appears to be effective for the worst case, fixed stick condition only.

IN-SIMULATOR FACTORIAL EXPERIMENT

After a description of the procedure used to collect the data, the results of the in-simulator experiment are presented.

Experimental Procedure

Four test subjects were used as sources of data at each of the 12 conditions in the DMS. A data collection period for each condition took about 3 minutes per run. The first 20 sec were used to phase in the sum of sines disturbance. The next 40 sec were used for subject stabilization, and the final 2 minutes were used for data collection. In order to encourage the subjects to do their best, their rms vertical tracking error scores were given to them after each simulation run.

Previous experiences suggested that 15 runs of the task were about the maximum number that could be made before the subject's performance began to deteriorate because of fatigue. A great deal of effort was expended in training each subject for each condition before data collection. Several sessions were used for each condition, until it appeared that the rms vertical tracking error had become "asymptotic" for that condition. At that point, seven replicates of data were recorded, and the training process for the next experimental condition began.

The test subjects used for this study were experienced simulation personnel rather than qualified pilots. This decision was deliberate and was based on the requirement for asymptotic performance for each of the 12 experimental conditions for each test subject. The previous studies (refs. 6 and 7) used active F-106 pilots, and lengthy training was required to achieve that performance requirement. It was felt that for this single-control-input tracking task and with the flexibility of the human operator model, the economic savings overrode any possible differences in test subjects.

In-Simulator Experiment Results

A summary of the results from an analysis of variance for each of the performance measures is presented in table V. Tables VI, VII, and VIII consist of means and standard deviations of these measures for each of the 12 conditions for each subject, and figure 6 presents the averages of the subjects for each measure. Also included in figure 6 are the in-simulator vertical-error results from reference 7. The present-study in-simulator results for the g-seat-off condition are better than the reference 7 in-simulator results, particularly for the worst case. The change in target motions allowed for this performance improvement. Subject differences between studies are presumed to be small.

The overall results of the present study show detectable performance differences between all main effects - subjects, simulator best and worst conditions, control loaders, and, for some measures, g-seat on and off conditions. These differences are usually more noticeable for the worst case condition.

The following detailed discussion of the results of the analyses of variance is based on the ordering of table V. Generally, there is a clear spread between individual subjects and also between the simulator (best and worst case) conditions. The significance of the subject by condition interaction reveals that the spread between subjects was much greater for the worst case condition.

The medium gradient stick generally produced lower vertical-tracking-error scores with less state and stick input activity. The values of all measures with the fixed stick were clearly separated from those of the movable sticks, as illustrated in figure 6. The subject by control loading interaction was significant, denoting differing subject sensitivities to stick changes. However, for each subject, stick change effects can be expressed as follows: measures with the medium gradient stick were less than or equal to measures with the light gradient stick, which were much less than the measures obtained with the fixed stick.

The significance of the condition by control loading interaction indicates that the spread between loaders was larger for the worst case condition (fig. 6), and the subject by condition by control loading interaction indicates that the differences in this spread across conditions varied from subject to subject.

The performance with the g-seat on was characterized by lower rms vertical tracking error, lower rms pitch, and lower rms altitude deviation. For the other measures, the subject by g-seat interaction was significant, and it reveals that some subjects were not sensitive to the g-seat condition, whereas others were sensitive. However, of those subjects that were sensitive to the g-seat condition, the sensitivity was revealed by either more or less of that measure. Hence, on the average, the g-seat effect was not evident for these measures. Both the main effect (the g-seat) and the subject by g-seat interaction were significant for the pitch measure, which indicates that although lower rms pitch was obtained when the g-seat was on for all the subjects, the effect was more pronounced for one particular subject.

The significance of the condition by g-seat interaction indicates that for those measures on which the g-seat had an effect, the effect appeared mainly for the worst case condition. The third-order interaction with subjects indicates the g-seat dependence on condition varied across subjects.

The control loader by g-seat interaction was significant for most measures. Generally, it indicates lower rms values with the g-seat on for the medium gradient stick, usually lower values or the same values for the fixed stick, and no consistent effects on performance for the light gradient stick. The significances of the third-order terms indicate, again, subject variability and larger effects for the worst case. The significance of the fourth-order term could be interpreted to mean that the subject variability to g-seat effect dependence on stick condition was different across best and worst conditions.

Of interest in the experimental results is the tendency for detectable differences to occur only under the more difficult task conditions. This finding concurs with current thinking (ref. 12) on trade-offs between simulation fidelity and cost being based on the specific flight task being simulated.

COMPARISON OF RESULTS

Combined plots of the untuned model predictions (fig. 5) and the in-simulator results (fig. 6) are presented in figure 7. Also, the model and in-simulator results from reference 7 are presented.

The in-simulator results demonstrate more sensitivity to the g-seat and to the fixed stick conditions than were predicted by the model. However, both control-loader and g-seat sensitivities are greater for the worst case, as predicted. In terms of other effect trends, the model predictions are upheld. In terms of rms magnitudes, however, the model predictions are off considerably, particularly for the best case vertical tracking error (which the ref. 7 results predict well). Also, all model values of pitch and normal acceleration were consistently lower than the in-simulator results.

Reference 8 suggests that some tuning of the pseudo-motor-rate noise of the operator model would possibly be necessary for the fixed stick configuration, and this clearly is necessary. Also necessary is some resolution of the differences in magnitudes of pitch and normal acceleration when stick input and, for the worst case, vertical tracking error match so well.

CONCLUDING REMARKS

The results from the in-simulator experiment demonstrate effectively the influence of simulation fidelity factors on man-machine system performance. Of particular interest is the change in performance error that can be attributed to the removal of stick-position and stick-rate feedback to the subject. The fixed stick configuration was identical to the medium gradient stick in everything but displacement, and yet performance differences were dramatic, being comparable to those obtained between "best" and "worst" conditions for the movable stick configurations.

Also of interest in the experimental results is the tendency for detectable differences to occur only under the more difficult task conditions. This finding concurs with current thinking on trade-offs between simulator fidelity and cost being based on the specific flight task being simulated.

The comparisons of model predictions with in-simulator results reveal that tuning of the model is desirable, particularly to obtain better matches with the "best" condition results. Previous in-simulator results, obtained before extensions were added to the facility model, predict the "best" condition more reliably. Also, the model predictions do not begin to account for the effect of the fixed stick on subject performance. Of particular concern too is the mismatch in the magnitudes of the plant states when the other states match.

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TABLE I.- MODEL SCORES FOR VARIOUS SIMULATOR CONFIGURATIONS

[From ref. 7]

Integration scheme	Sample frequency, Hz	Visual servo bandwidth, rad/sec	Control loader	Observed noise-to-signal ratio, dB	rms vertical tracking error, ft
Euler	32	∞	Analog	-17	9.65
↓	↓	25	Analog	↓	10.41
↓	↓	∞	Digital	↓	9.96
↓	↓	25	Digital	↓	10.70
2nd-order Adams-Bashforth	16	∞	Analog	↓	9.32
↓	↓	25	Analog	↓	10.11
↓	↓	∞	Digital	↓	10.16
↓	↓	25	Digital	↓	10.90
↓	32	∞	Analog	↓	8.99
↓	↓	25	Analog	↓	9.79
↓	↓	∞	Digital	↓	8.60
↓	↓	25	Digital	↓	9.45
Euler	16	25	Analog	-11	15.18
↓	↓	∞	Analog	↓	14.56
↓	↓	25	Digital	↓	15.83
↓	↓	∞	Digital	↓	15.25

TABLE II.- COMPARISON OF MODEL AND EXPERIMENTAL RESULTS

[From ref. 7]

Configuration	rms vertical tracking error,[a] ft, for -		
	Model runs 1 to 16	Model runs 5 to 20	Experiment
Integration scheme:			
Euler	10.76 ± 0.74	12.69 ± 2.50	12.67 ± 3.19
2nd-order Adams-Bashforth	9.67 ± 0.68	9.67 ± 0.68	9.69 ± 1.59
Sample frequency:			
16 Hz	10.72 ± 0.81	12.66 ± 2.60	12.57 ± 3.11
32 Hz	9.69 ± 0.65	9.69 ± 0.65	9.79 ± 1.89
Visual servo bandwidth:			
25 rad/sec	10.59 ± 0.79	11.55 ± 2.33	12.26 ± 2.90
∞	9.83 ± 0.83	10.81 ± 2.41	10.10 ± 2.52
Control loader:			
Digital	10.49 ± 0.91	11.45 ± 2.43	11.35 ± 2.83
Analog	9.93 ± 0.60	10.91 ± 2.36	11.01 ± 3.02
Implementation condition:			
Worst	11.69 ± 0.52	15.50 ± 0.46	16.27 ± 2.08
Best	8.80 ± 0.28	8.80 ± 0.28	8.39 ± 0.97

[a]Mean ±1 standard deviation.

TABLE III.- PARAMETERS OF SUM OF SINE WAVES

Frequency, rad/sec	Relative amplitude[a]
0.245	1.02900
.540	.80700
.933	.49200
1.424	.21600
2.013	.09390
2.896	.04140
4.074	.01750
5.547	.00793
8.001	.00344
10.946	.00149
16.248	.000614
22.040	.000255
32.094	.000108

[a]Without scale factor of 20 ft.

TABLE IV.- PARAMETERS OF OPTIMAL CONTROL MODEL

Configuration	Best condition	Worst condition
Time delay, sec	0.288	0.391
Neuromotor time constant, sec	0.12	0.15
Observed noise-to-signal ratio, dB	-17	-11
Pseudo-motor-rate-noise ratio, dB	-30	-30

TABLE V.- ANALYSES OF VARIANCE FOR THE IN-SIMULATOR EXPERIMENT

Factor (a)	Degrees of freedom	Significance[b] of -					
		rms vertical tracking error	rms vertical tracking error rate	rms pitch	rms normal acceleration	rms altitude deviation	rms stick input
S	3	**	**	**	**	**	**
C	1	**	**	**	**	**	**
S × C	3	**	**	**	**	-	**
L	2	**	**	**	**	**	**
S × L	6	**	**	**	**	**	**
C × L	2	**	**	**	**	**	*
S × C × L	6	**	**	**	**	-	**
G	1	**	-	*	-	*	-
S × G	3	-	**	**	**	-	**
C × G	1	**	-	**	*	*	-
S × C × G	3	**	**	**	**	**	**
L × G	2	**	**	**	**	-	-
S × L × G	6	**	**	**	**	**	**
C × L × G	2	-	**	-	**	-	*
S × C × L × G	6	**	-	**	**	-	**

[a]Factors are as follows: S - subject; C - simulator condition; L - control-loading system; G - g-seat.
[b]Significance shown as follows:
- \- not significant at levels considered.
- * significant at 5 percent level.
- ** significant at 1 percent level.

TABLE VI.- SUBJECT PERFORMANCES WITH LIGHT GRADIENT STICK

Subject	Simulator condition	g-seat	Vertical tracking error, ft		Vertical-tracking-error rate, ft/sec		Pitch, deg		Normal acceleration, g units		Altitude deviation, ft		Stick input, deg	
			Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	Best	Off	9.535	0.652	18.805	0.761	2.03	0.05	0.40	0.01	26.651	0.558	0.76	0.02
		On	10.358	0.429	18.064	0.440	2.02	0.03	0.39	0.01	27.232	0.518	0.75	0.01
	Worst	Off	17.700	0.253	26.574	1.420	2.55	0.09	0.52	0.02	31.423	0.562	0.92	0.04
		On	16.648	0.300	27.402	2.274	2.45	0.06	0.51	0.02	30.971	0.952	0.88	0.03
2	Best	Off	8.815	0.420	16.033	0.863	1.77	0.04	0.33	0.01	26.391	0.570	0.67	0.02
		On	9.905	0.756	16.374	1.062	1.80	0.04	0.33	0.01	27.277	0.698	0.67	0.02
	Worst	Off	14.497	0.626	20.352	1.158	2.03	0.04	0.39	0.01	30.284	0.641	0.74	0.01
		On	16.934	1.132	25.426	3.363	2.18	0.07	0.43	0.01	31.721	1.225	0.80	0.03
3	Best	Off	7.158	0.539	17.624	0.468	1.77	0.04	0.34	0.01	25.154	0.328	0.70	0.02
		On	7.316	0.286	17.795	0.294	1.73	0.03	0.34	0.01	24.899	0.337	0.70	0.02
	Worst	Off	12.958	0.519	23.414	0.788	2.16	0.04	0.44	0.01	28.537	0.716	0.81	0.02
		On	13.465	0.635	26.855	1.787	2.16	0.07	0.45	0.02	29.091	0.893	0.86	0.02
4	Best	Off	7.505	0.362	16.826	0.643	1.82	0.03	0.35	0.01	25.637	0.533	0.69	0.01
		On	7.819	0.383	16.944	0.882	1.86	0.05	0.36	0.01	25.602	0.402	0.69	0.02
	Worst	Off	15.666	0.697	21.157	1.177	2.29	0.08	0.45	0.02	31.207	1.071	0.83	0.04
		On	13.521	0.785	20.780	2.096	2.20	0.06	0.44	0.02	28.910	0.751	0.80	0.03
Average	Best	Off	8.253	1.091	17.322	1.234	1.85	0.12	0.36	0.04	25.958	0.772	0.72	0.05
		On	8.850	1.408	17.294	0.978	1.85	0.12	0.36	0.03	26.253	1.155	0.72	0.04
	Worst	Off	15.205	1.838	22.874	2.689	2.26	0.21	0.46	0.06	30.363	1.368	0.84	0.07
		On	15.142	1.834	25.116	3.519	2.25	0.14	0.44	0.04	30.173	1.530	0.82	0.07

TABLE VII.- SUBJECT PERFORMANCES WITH MEDIUM GRADIENT STICK

Subject	Simulator condition	g-seat	Vertical tracking error, ft		Vertical-tracking-error rate, ft/sec		Pitch, deg		Normal acceleration, g units		Altitude deviation, ft		Stick input, deg	
			Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	Best	Off	9.932	0.459	20.139	0.237	2.14	0.01	0.43	0.01	26.881	0.289	0.81	0.01
		On	9.450	0.349	18.637	0.490	2.07	0.04	0.41	0.01	26.771	0.332	0.78	0.02
	Worst	Off	17.183	0.681	28.935	2.060	2.60	0.10	0.55	0.02	30.506	0.699	0.95	0.04
		On	16.653	0.485	24.938	0.933	2.50	0.07	0.51	0.02	31.102	0.713	0.91	0.03
2	Best	Off	10.905	0.564	16.977	0.935	1.85	0.05	0.34	0.02	27.908	0.463	0.69	0.03
		On	8.600	0.340	16.082	0.294	1.77	0.04	0.33	0.01	26.267	0.334	0.67	0.01
	Worst	Off	15.174	1.029	21.460	1.507	2.15	0.07	0.41	0.02	31.324	1.045	0.78	0.03
		On	13.093	0.652	21.532	2.680	2.06	0.06	0.41	0.02	29.352	0.872	0.79	0.04
3	Best	Off	6.147	0.417	17.108	0.487	1.73	0.03	0.34	0.01	24.518	0.522	0.70	0.01
		On	6.936	0.324	18.285	0.490	1.74	0.02	0.34	0.01	25.031	0.171	0.72	0.01
	Worst	Off	12.621	0.527	24.578	0.634	2.10	0.05	0.43	0.01	28.162	0.882	0.82	0.02
		On	12.322	0.636	24.513	0.973	2.08	0.07	0.43	0.01	28.132	0.629	0.82	0.03
4	Best	Off	7.171	0.442	16.560	0.427	1.81	0.04	0.35	0.01	25.376	0.392	0.69	0.01
		On	8.656	0.439	18.268	0.687	1.92	0.03	0.37	0.01	26.134	0.564	0.73	0.01
	Worst	Off	14.695	0.427	20.159	0.760	2.22	0.07	0.43	0.02	29.270	3.822	0.80	0.03
		On	12.457	0.300	19.010	0.762	2.06	0.06	0.41	0.01	28.292	0.690	0.75	0.03
Average	Best	Off	8.539	2.031	17.696	1.551	1.88	0.16	0.36	0.03	26.171	1.395	0.71	0.04
		On	8.410	0.994	17.818	1.138	1.87	0.14	0.35	0.03	26.051	0.738	0.70	0.03
	Worst	Off	14.918	1.780	23.783	3.676	2.27	0.21	0.45	0.05	29.815	2.296	0.83	0.05
		On	13.631	1.871	22.498	2.849	2.18	0.20	0.46	0.04	29.220	1.389	0.84	0.05

TABLE VIII.- SUBJECT PERFORMANCES WITH FIXED GRADIENT STICK

Subject	Simulator condition	g-seat	Vertical tracking error, ft		Vertical-tracking-error rate, ft/sec		Pitch, deg		Normal acceleration, g units		Altitude deviation, ft		Stick input, deg	
			Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	Best	Off	11.947	0.614	22.927	1.172	2.14	0.06	0.43	0.02	27.869	0.493	0.81	0.03
		On	11.962	0.293	22.965	1.324	2.18	0.04	0.44	0.01	27.815	0.456	0.86	0.02
	Worst	Off	20.074	0.567	28.046	1.982	2.74	0.06	0.56	0.02	33.547	1.067	0.99	0.02
		On	19.354	0.792	27.770	1.898	2.66	0.09	0.55	0.02	33.138	1.310	0.95	0.03
2	Best	Off	12.556	0.550	23.090	2.464	1.95	0.04	0.38	0.01	28.448	0.681	0.83	0.06
		On	11.026	0.454	19.796	1.272	2.00	0.05	0.39	0.01	27.407	0.436	0.77	0.02
	Worst	Off	19.972	0.546	25.943	1.816	2.48	0.13	0.50	0.03	33.852	0.724	0.89	0.05
		On	19.141	0.651	23.507	1.835	2.42	0.08	0.47	0.03	34.393	1.180	0.86	0.03
3	Best	Off	9.571	0.485	17.671	0.761	1.87	0.04	0.36	0.01	26.818	0.629	0.71	0.02
		On	9.268	0.454	18.103	1.197	1.88	0.06	0.36	0.02	26.617	0.341	0.72	0.02
	Worst	Off	18.337	1.140	20.252	0.890	2.21	0.05	0.42	0.01	33.406	1.201	0.78	0.02
		On	16.980	1.049	20.869	1.005	2.23	0.06	0.43	0.02	32.253	0.823	0.80	0.03
4	Best	Off	9.707	0.272	18.832	0.843	1.84	0.02	0.36	0.01	26.622	0.517	0.70	0.01
		On	10.485	0.382	18.574	1.342	1.91	0.03	0.37	0.01	27.150	0.413	0.71	0.02
	Worst	Off	19.120	0.314	25.508	2.287	2.48	0.04	0.50	0.02	33.788	1.057	0.87	0.02
		On	18.479	1.098	24.987	1.280	2.51	0.09	0.51	0.02	32.587	0.979	0.90	0.04
Average	Best	Off	10.945	1.428	20.630	2.826	1.95	0.13	0.38	0.03	27.439	0.943	0.76	0.07
		On	10.685	1.062	19.859	2.280	1.99	0.13	0.39	0.03	27.247	0.590	0.76	0.06
	Worst	Off	19.376	0.982	24.937	3.389	2.48	0.20	0.49	0.06	33.648	0.986	0.88	0.08
		On	18.489	1.281	24.283	2.932	2.46	0.18	0.49	0.05	33.093	1.320	0.88	0.06

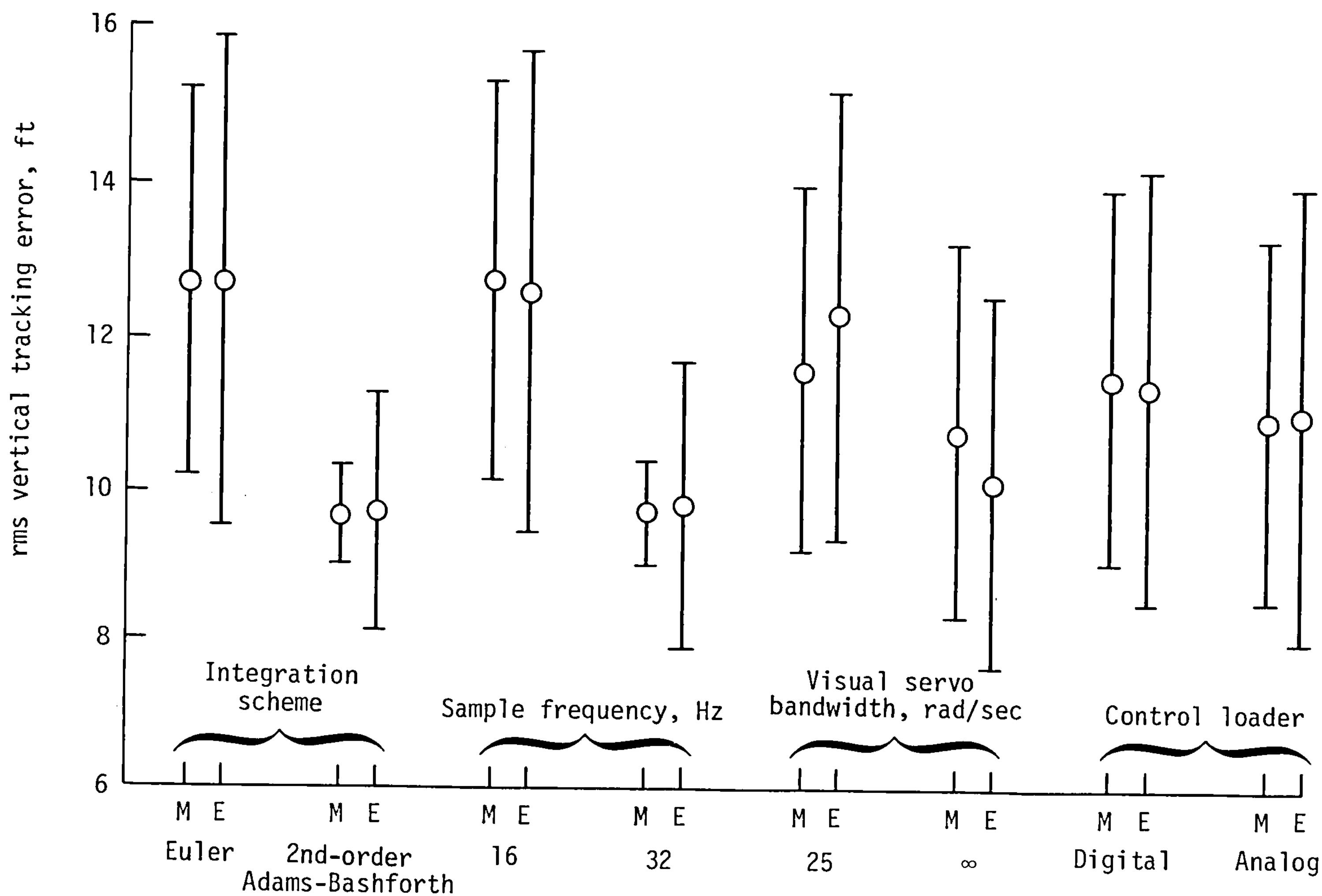
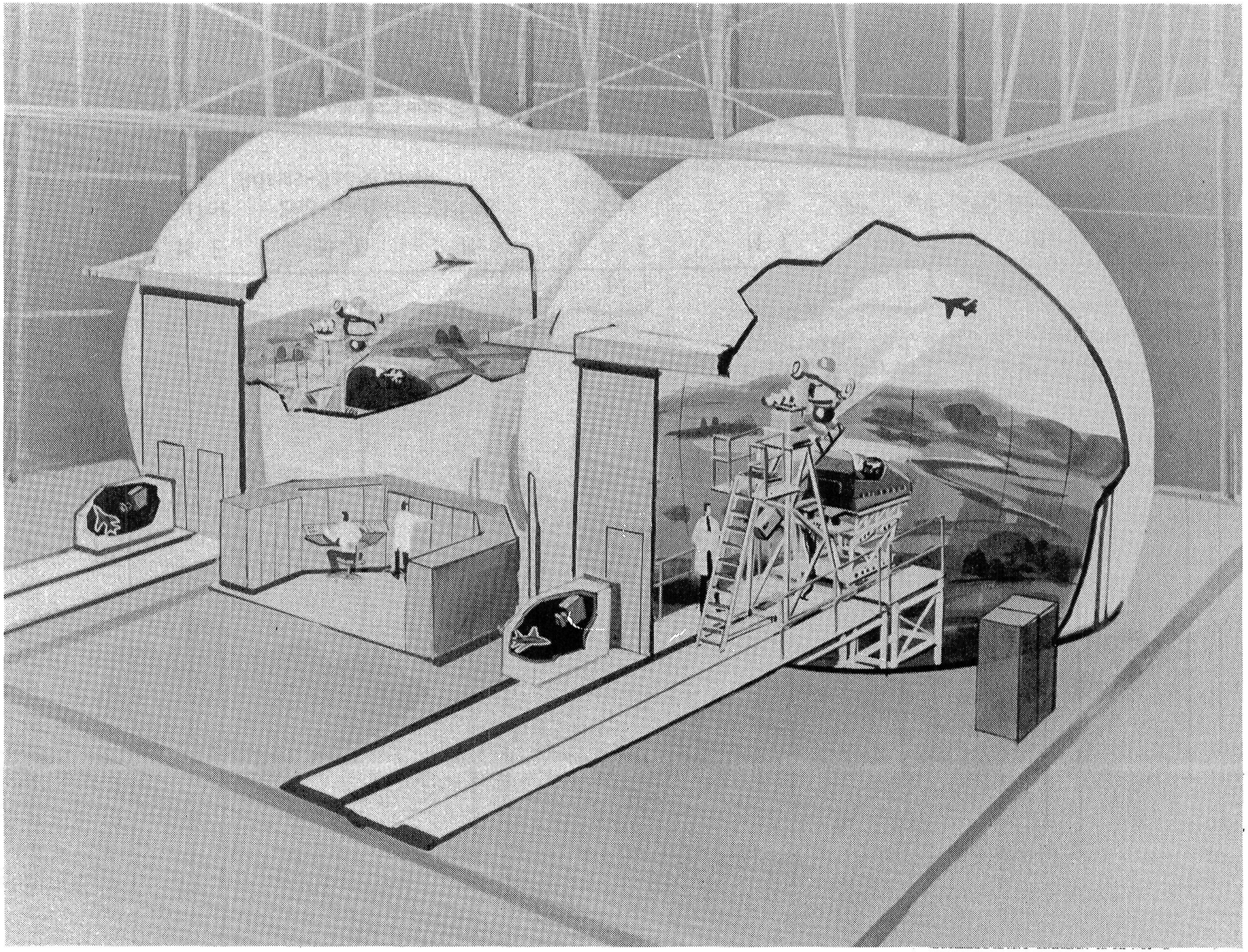


Figure 1.- Comparison of model (M) and experimental (E) tracking error (from ref. 7).



L-71-8700

Figure 2.- Setup of Langley Differential Maneuvering Simulator.

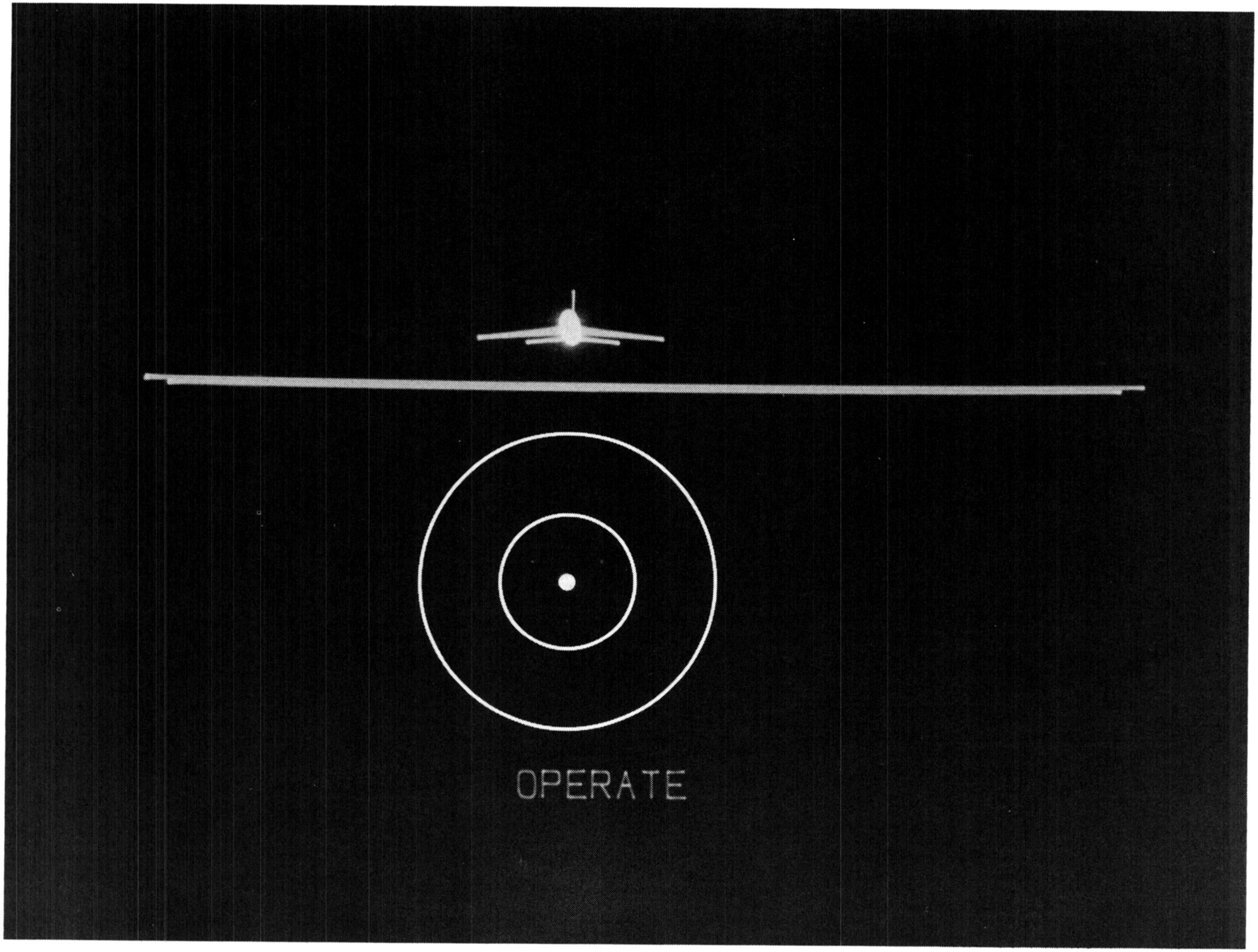


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Figure 3.- Head-up display presented to pilots.

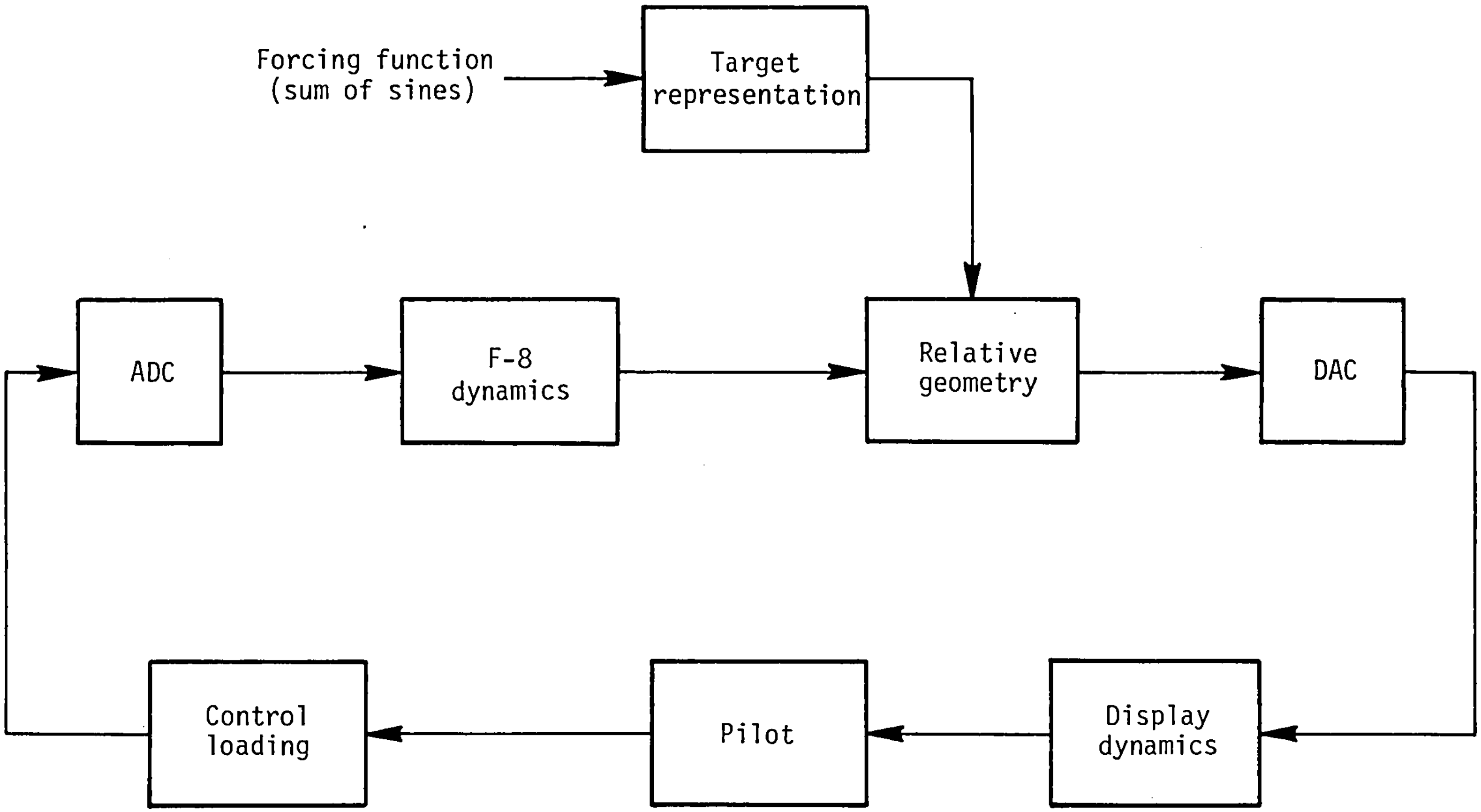
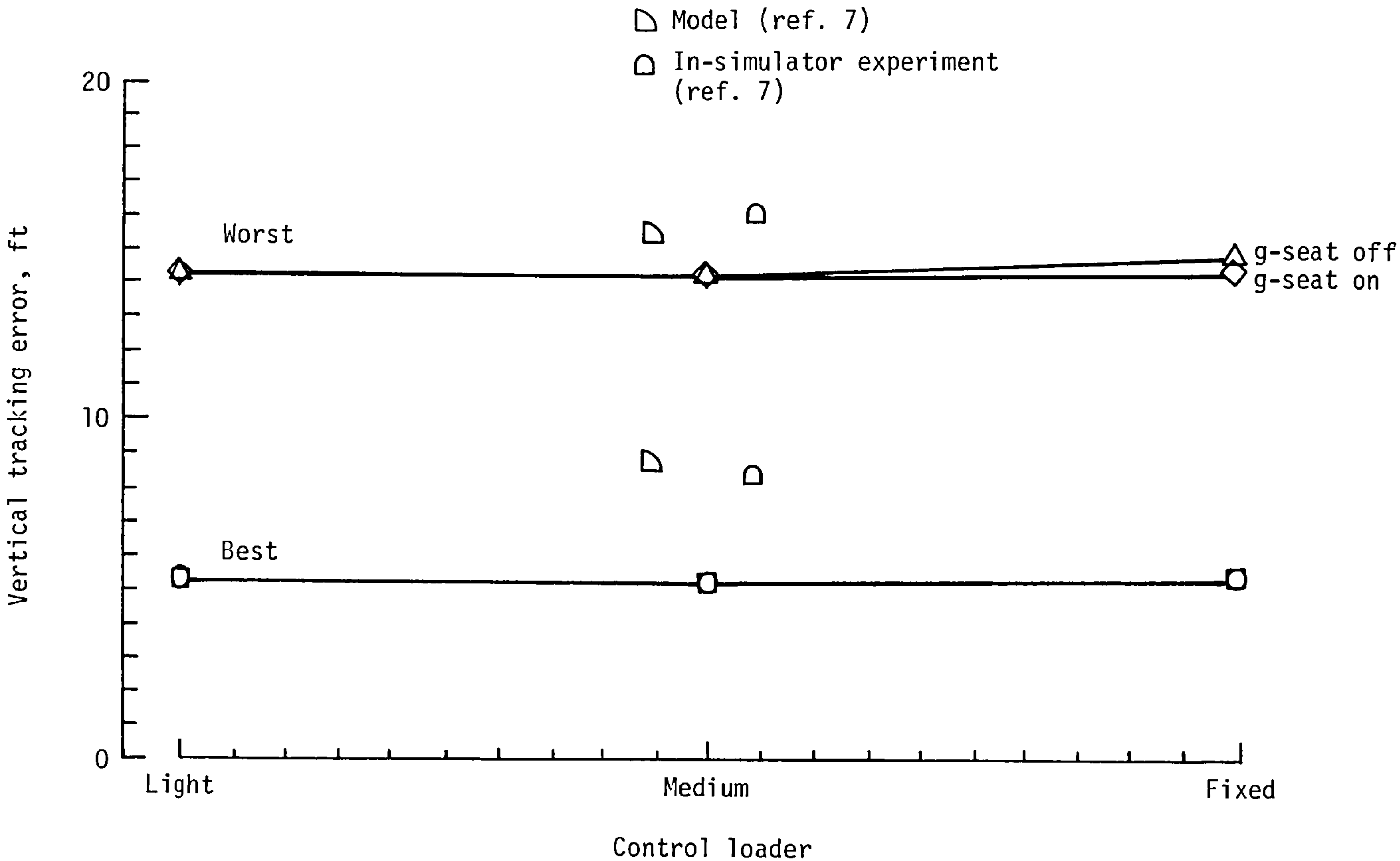
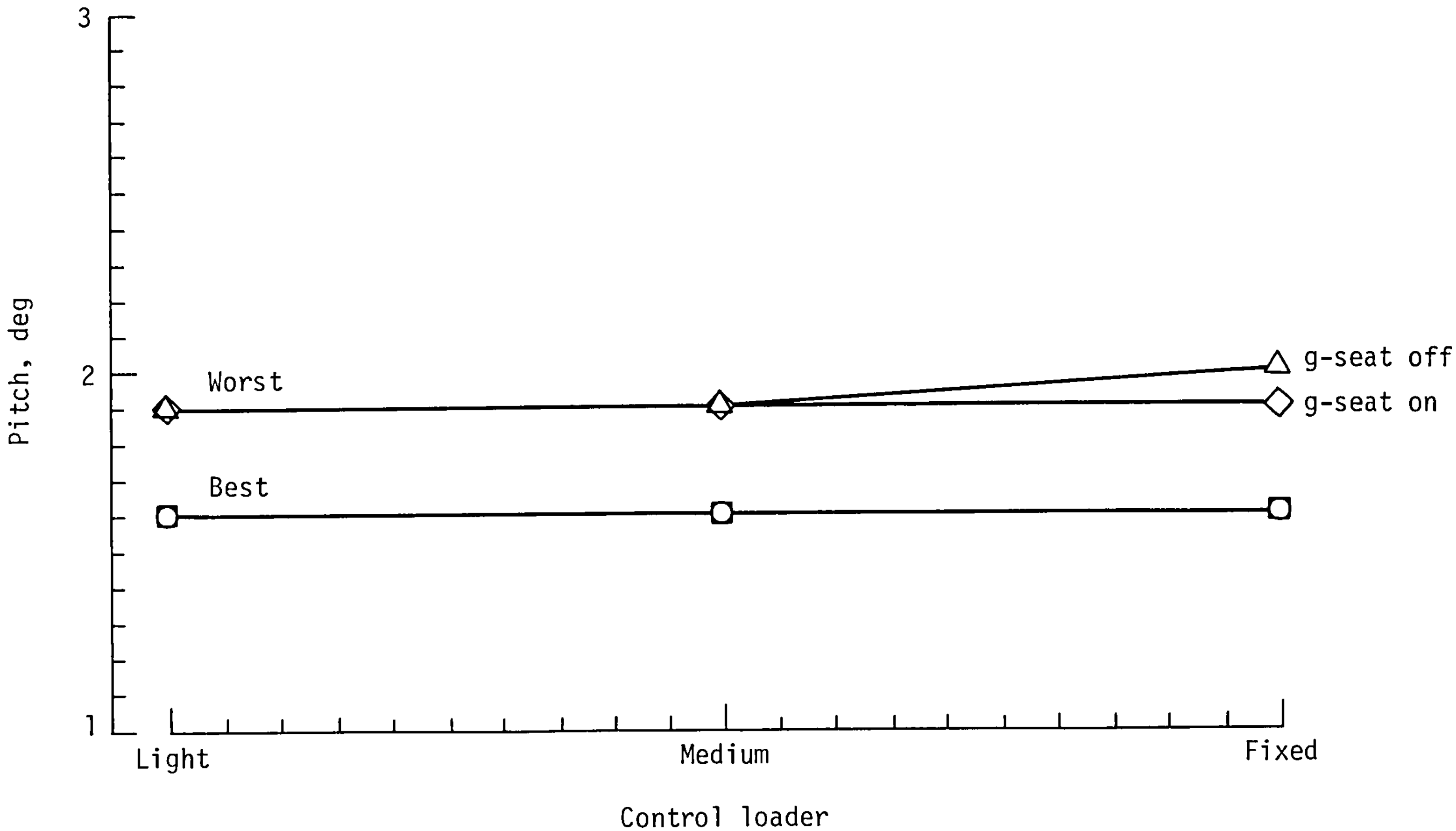


Figure 4.- Closed-loop components of single-axis, multiloop, compensatory-pitch tracking task.



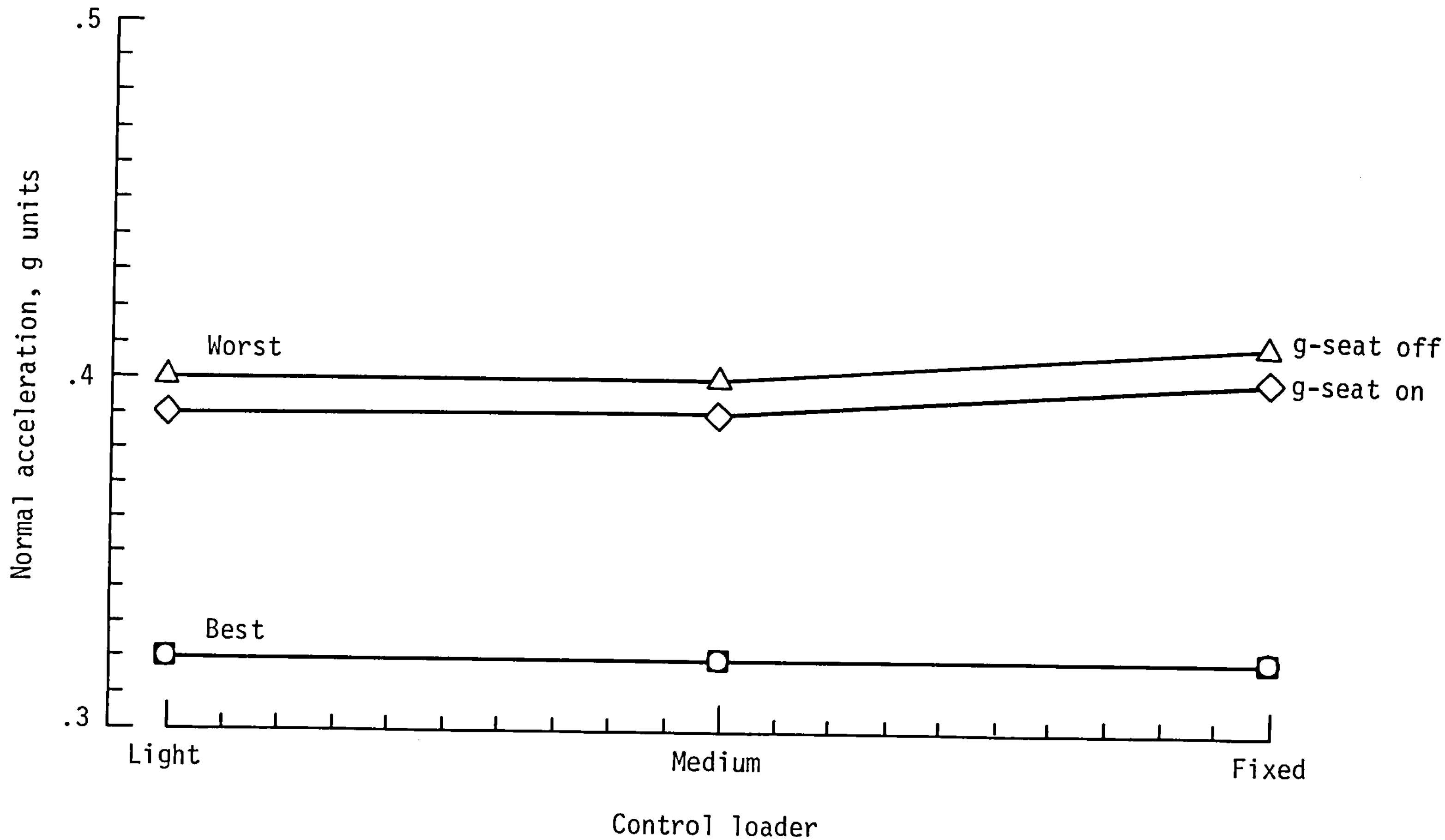
(a) Vertical-tracking-error predictions.

Figure 5.- Untuned model predictions of pilot-simulator performance.



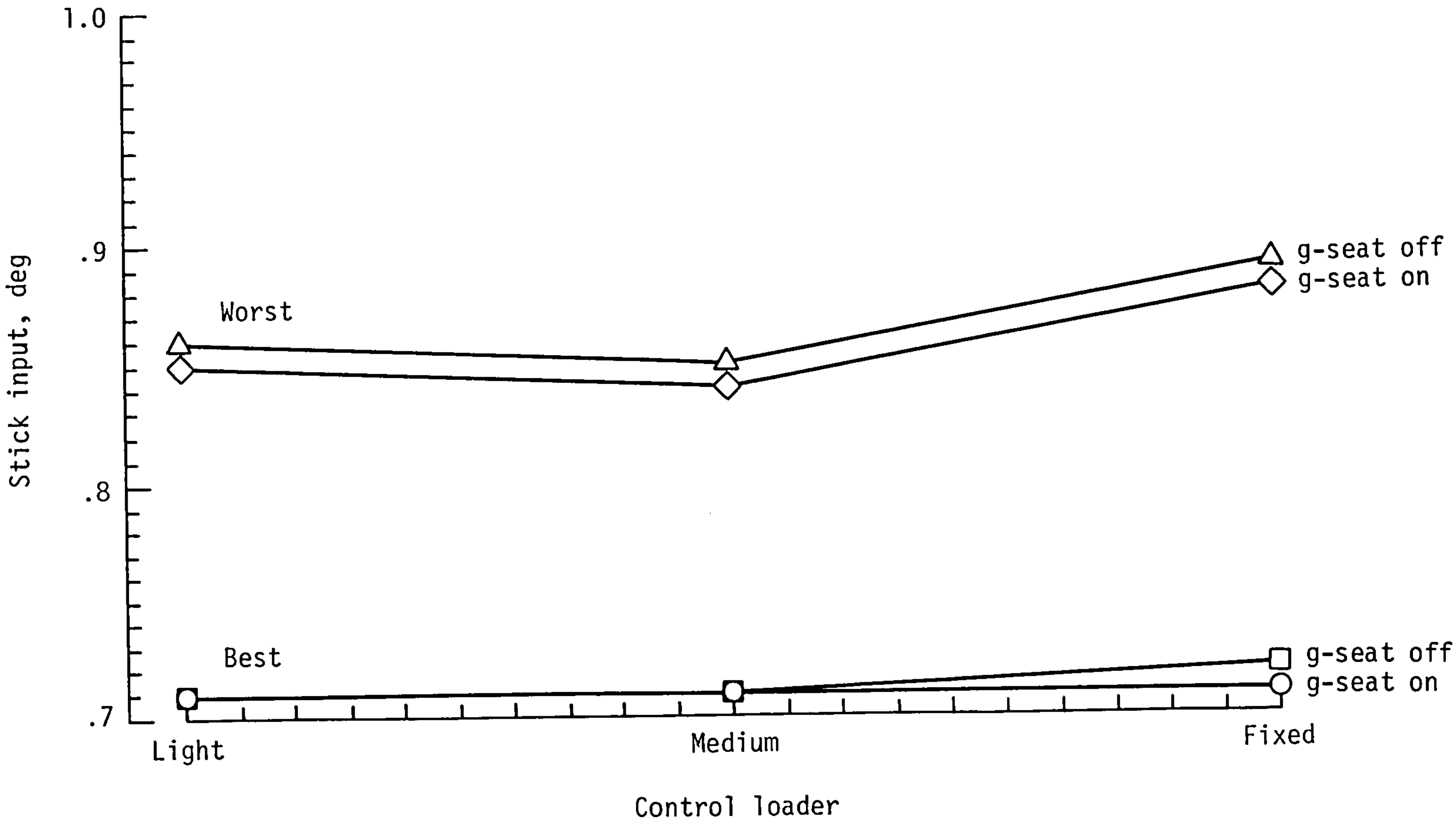
(b) Pitch predictions.

Figure 5.- Continued.



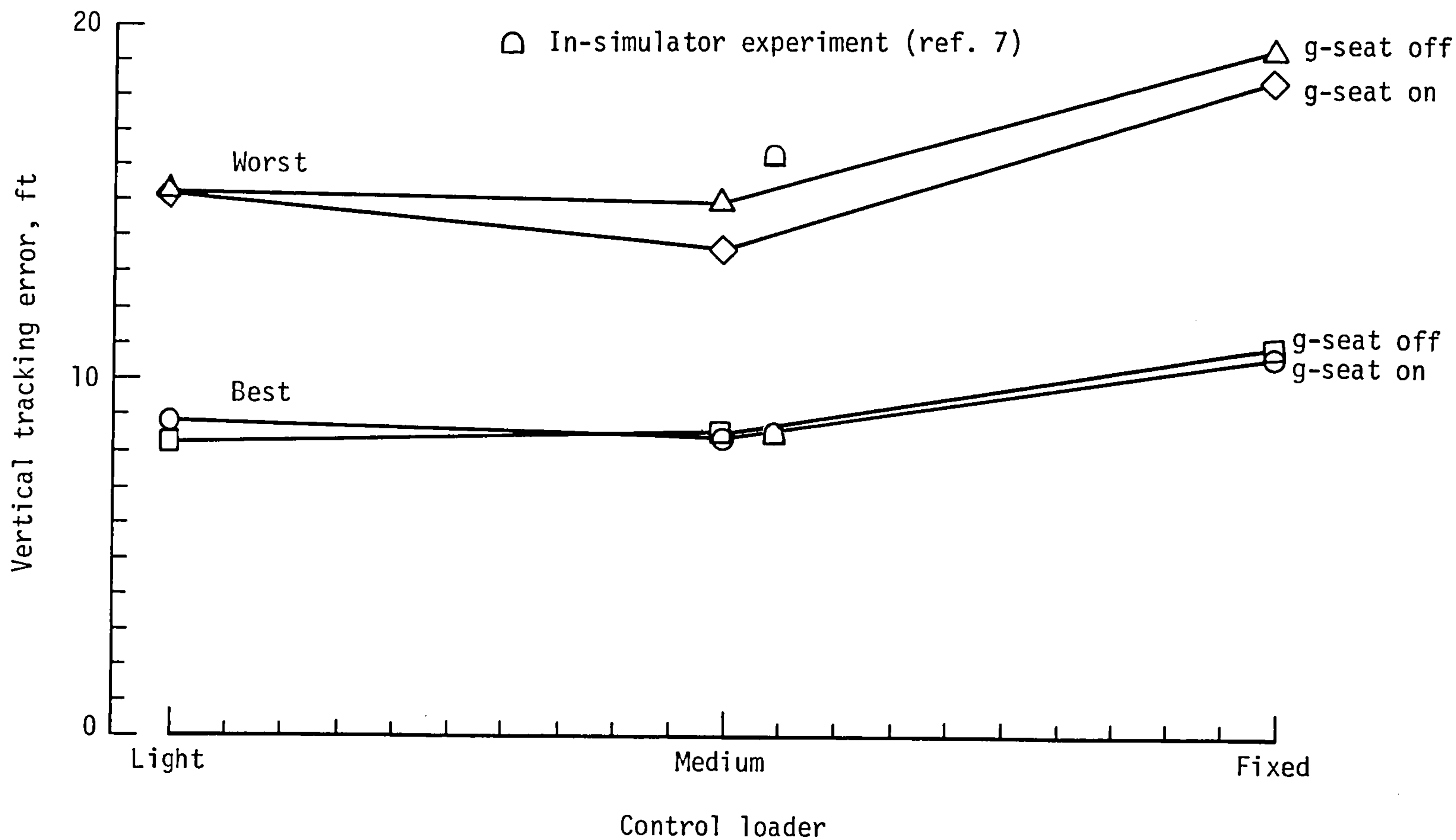
(c) Normal acceleration predictions.

Figure 5.- Continued.



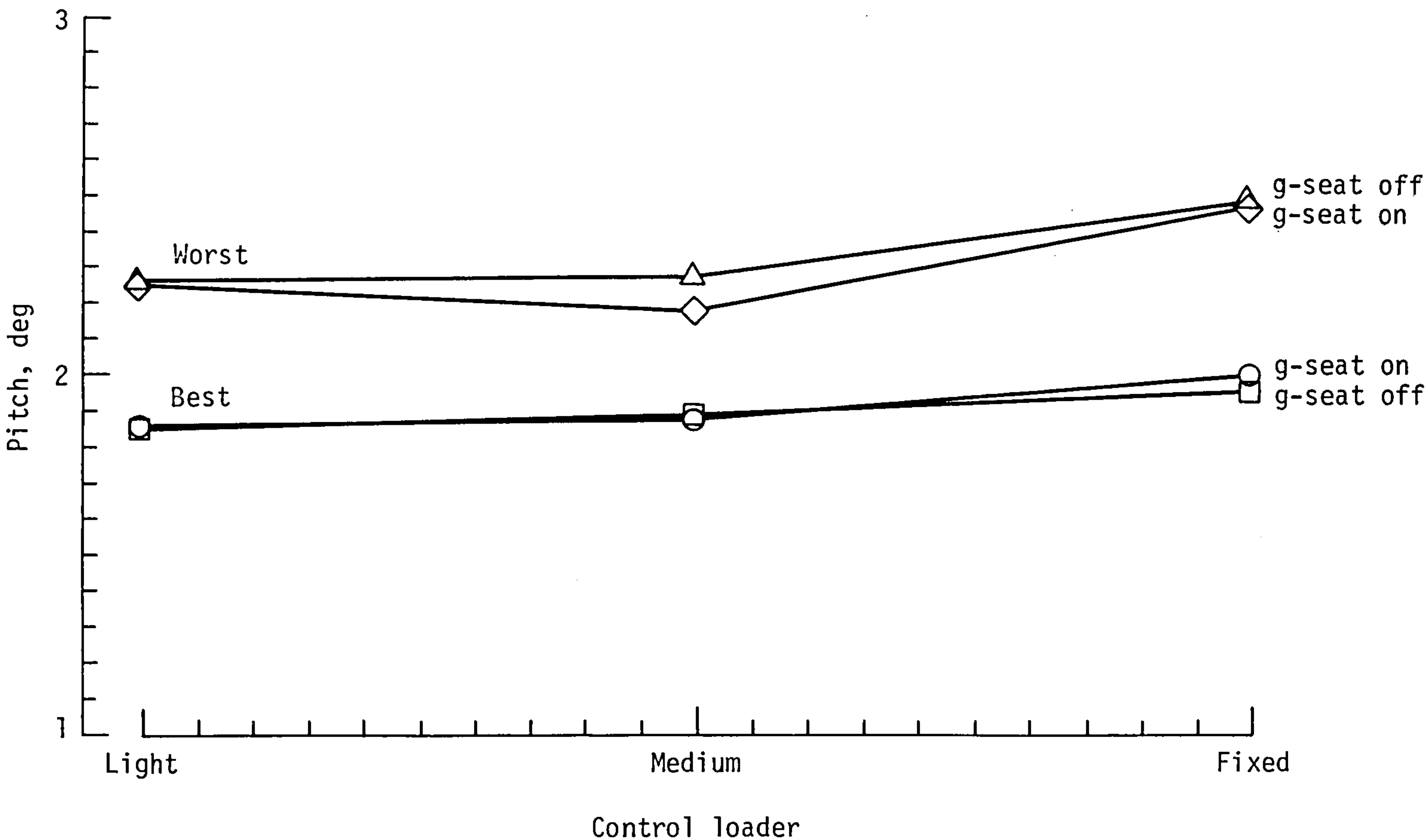
(d) Stick input predictions.

Figure 5.- Concluded.



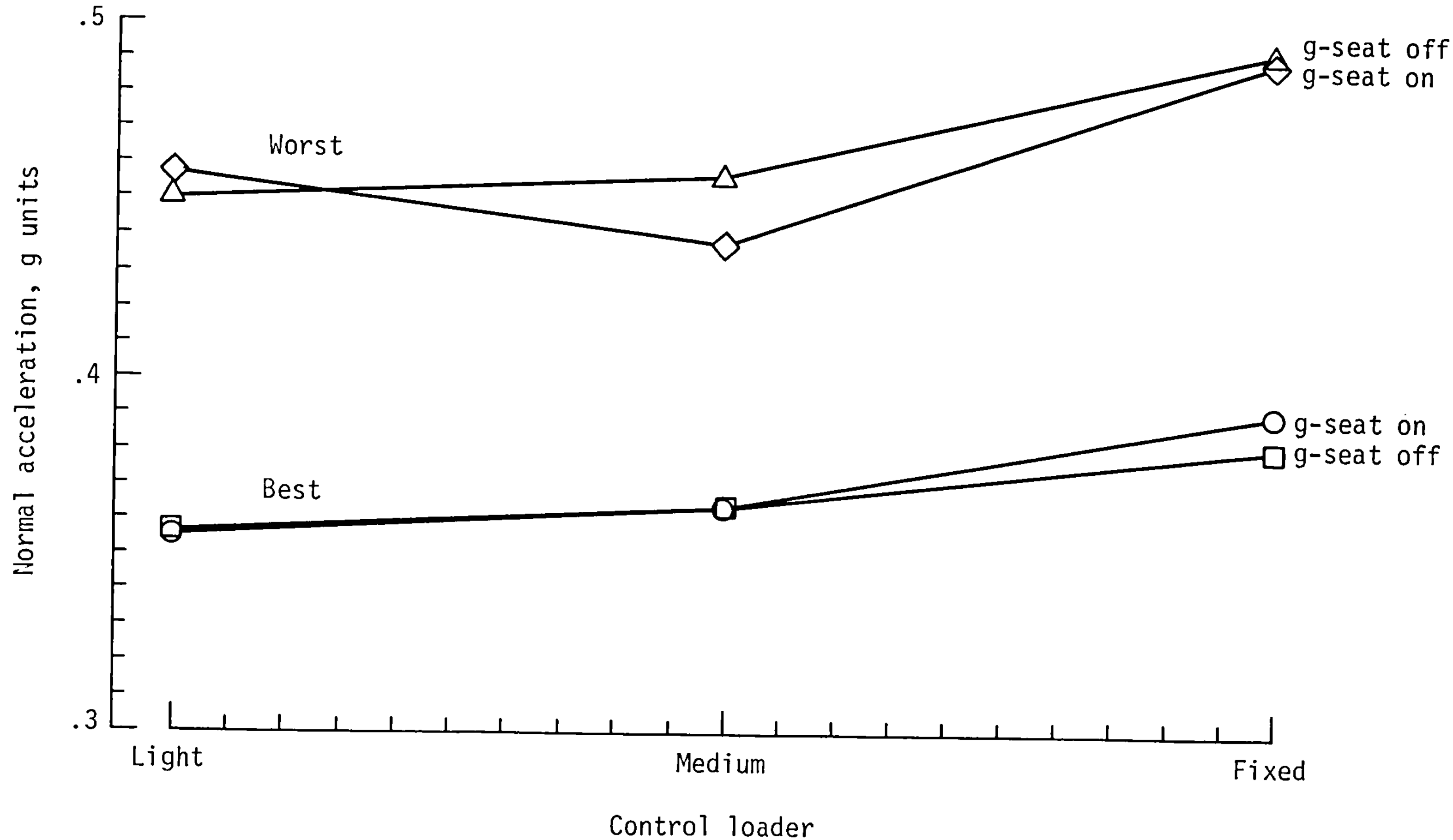
(a) Vertical-tracking-error results.

Figure 6.- In-simulator pilot-vehicle performance results.



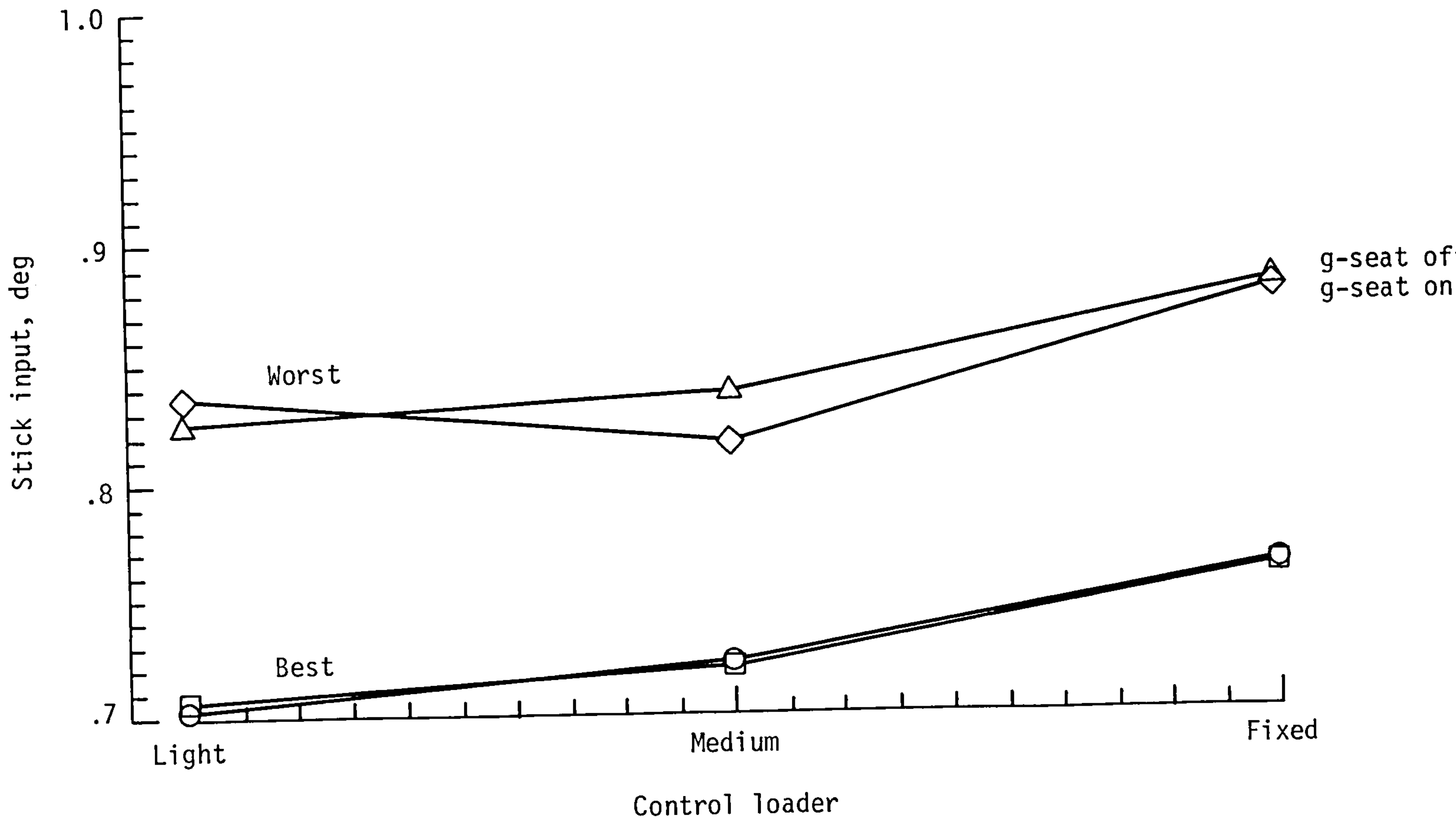
(b) Pitch results.

Figure 6.- Continued.



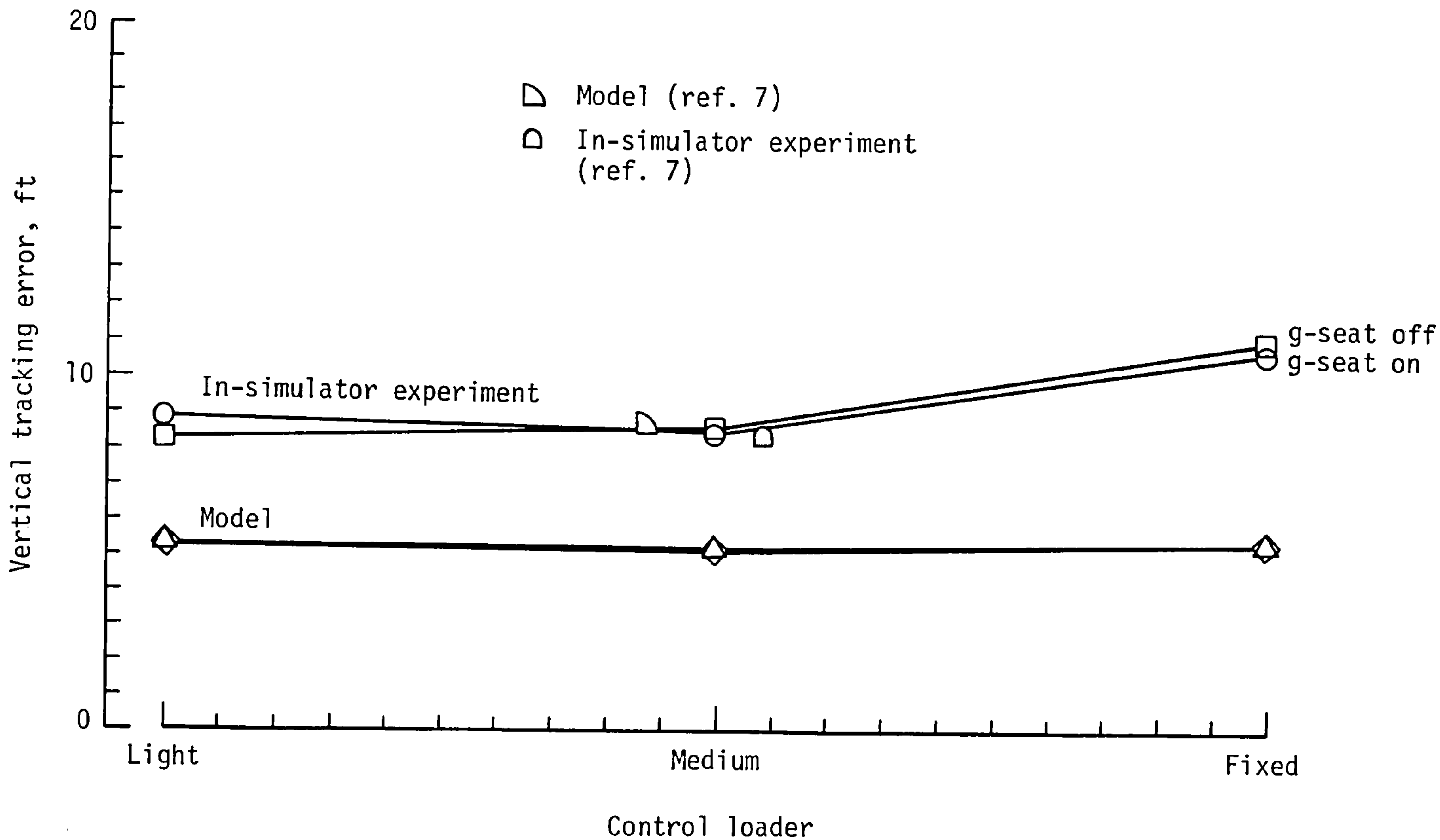
(c) Normal acceleration results.

Figure 6.- Continued.



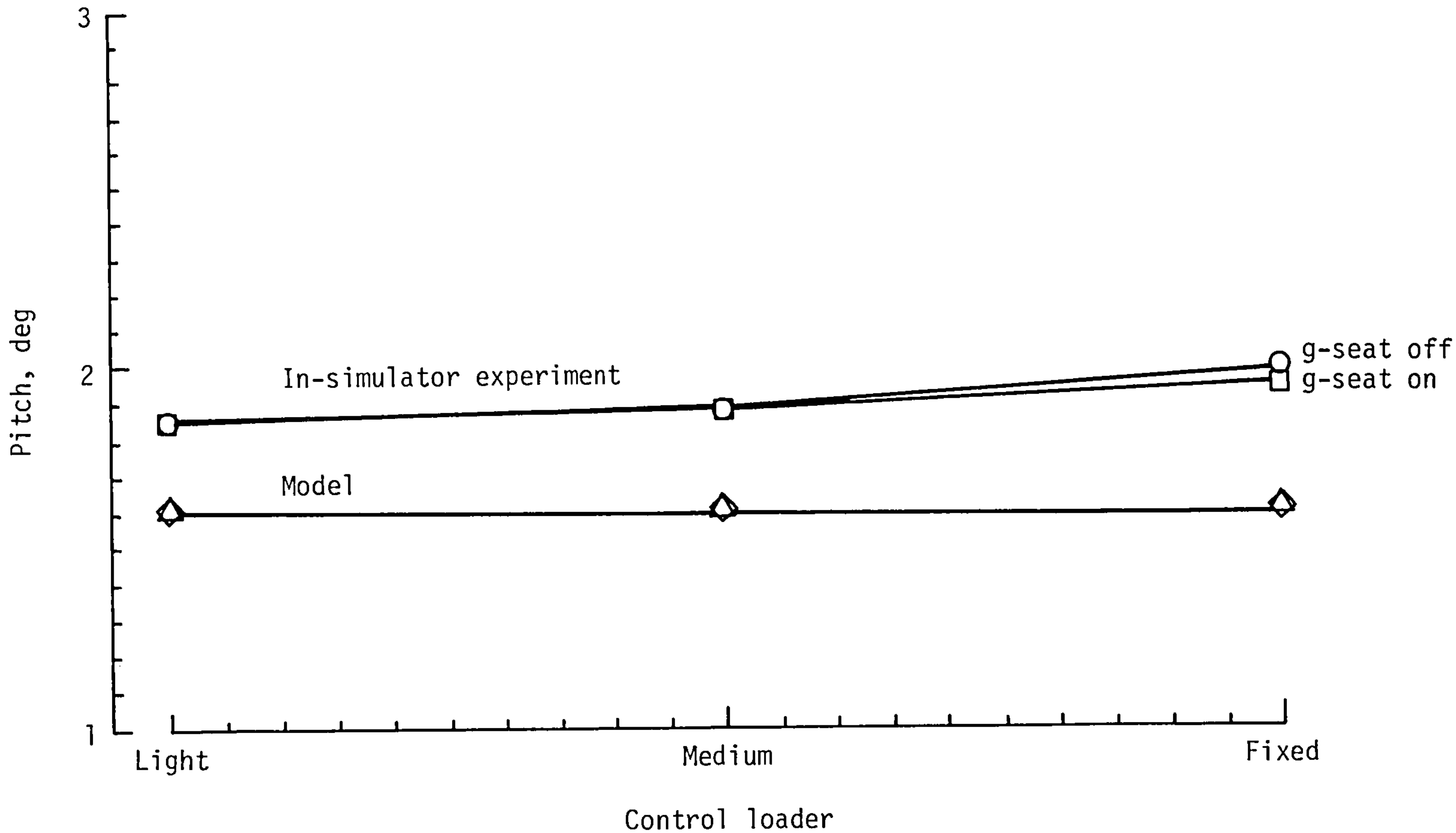
(d) Stick input results.

Figure 6.- Concluded.



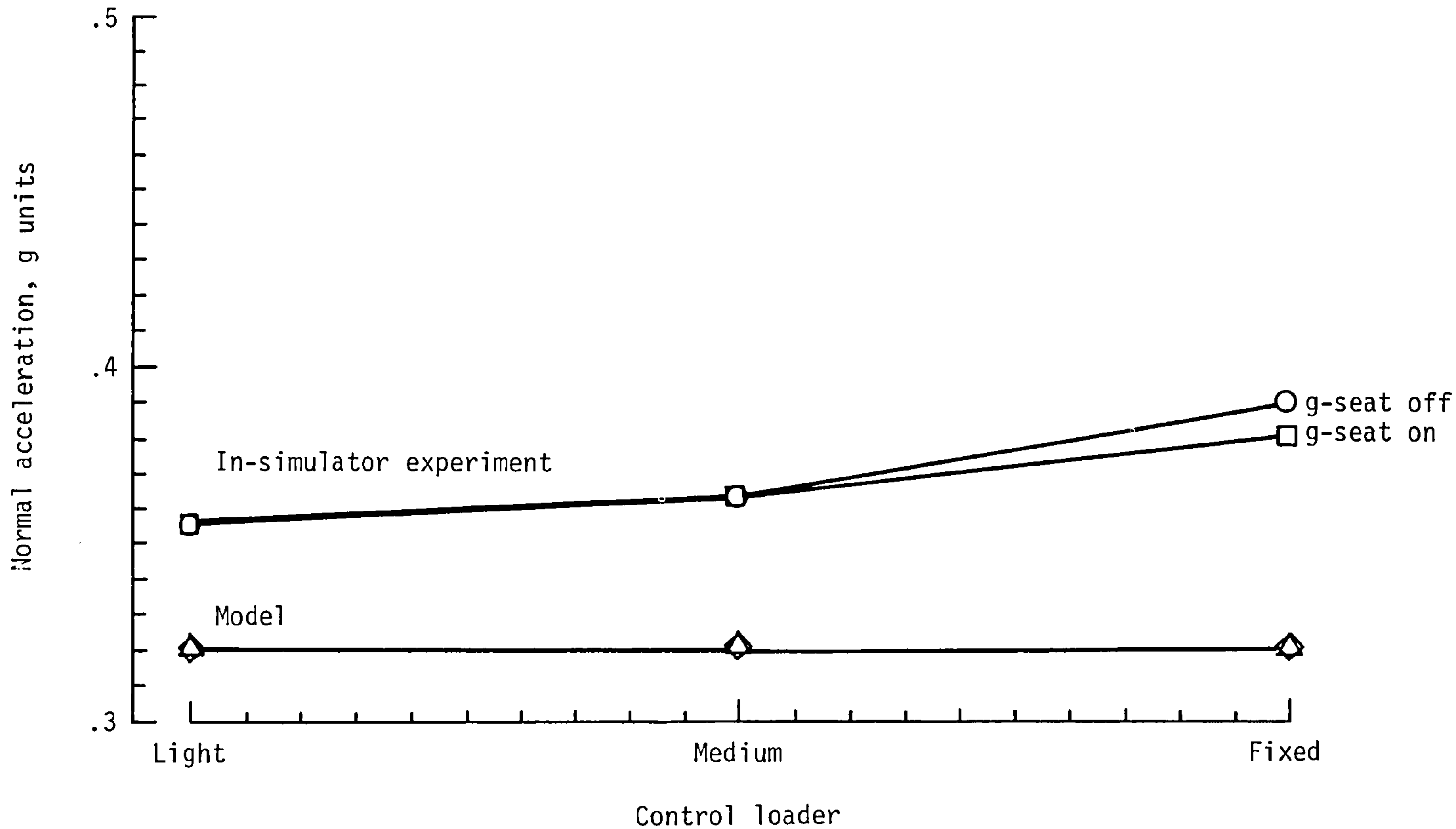
(a) Vertical-tracking-error results for "best" condition.

Figure 7.- Comparison of model predictions with in-simulator results.



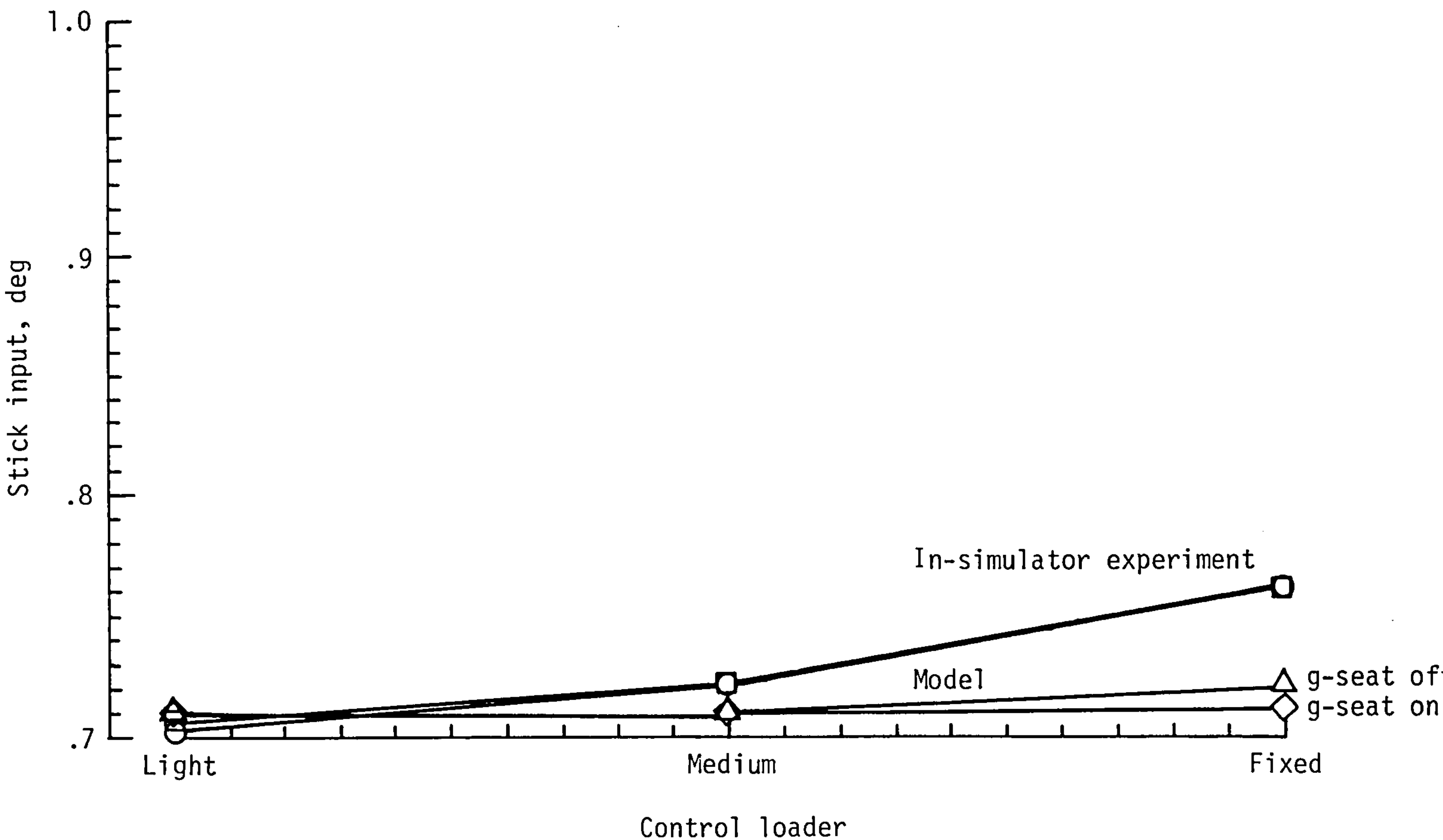
(b) Pitch results for "best" condition.

Figure 7.- Continued.



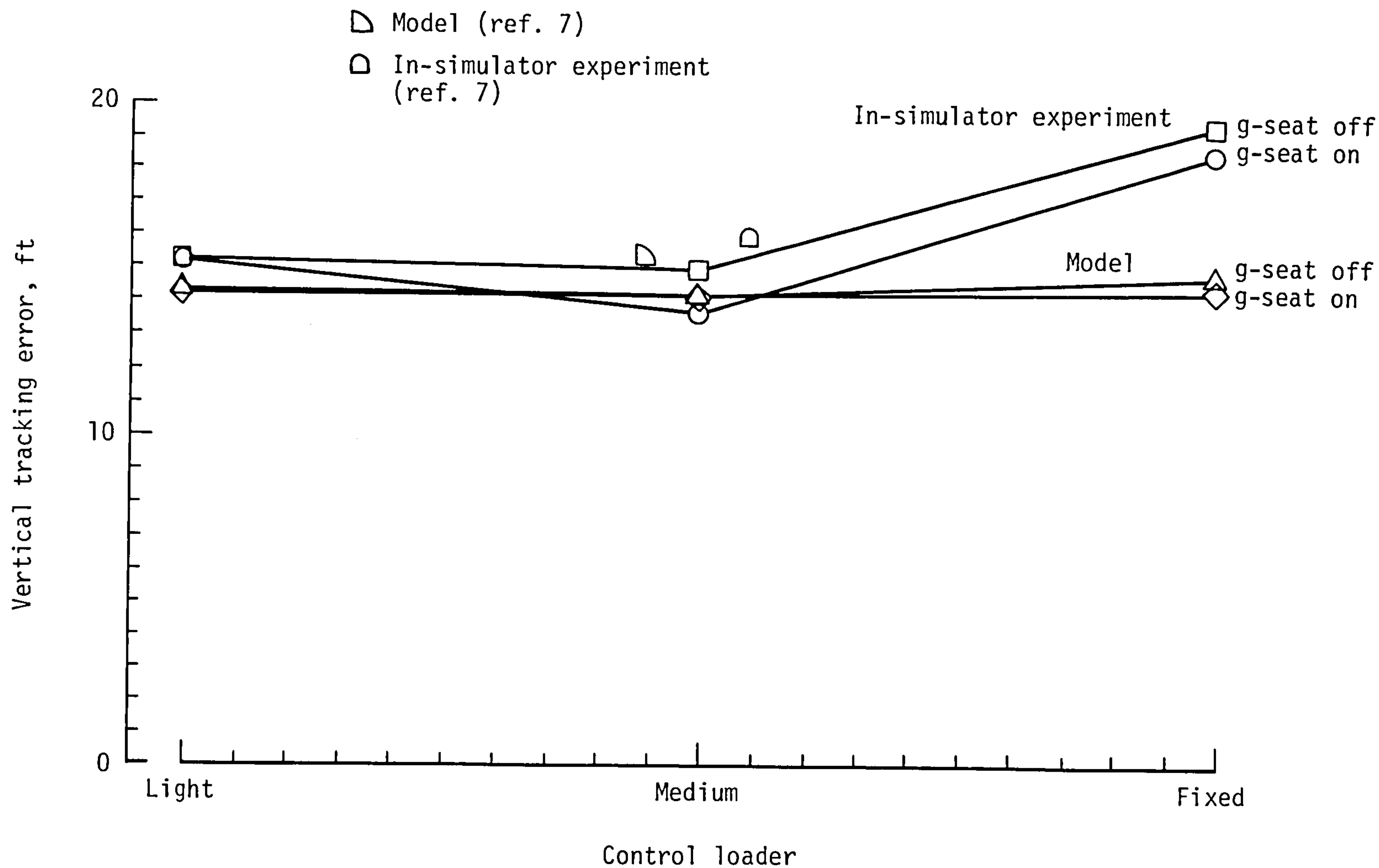
(c) Normal acceleration results for "best" condition.

Figure 7.- Continued.



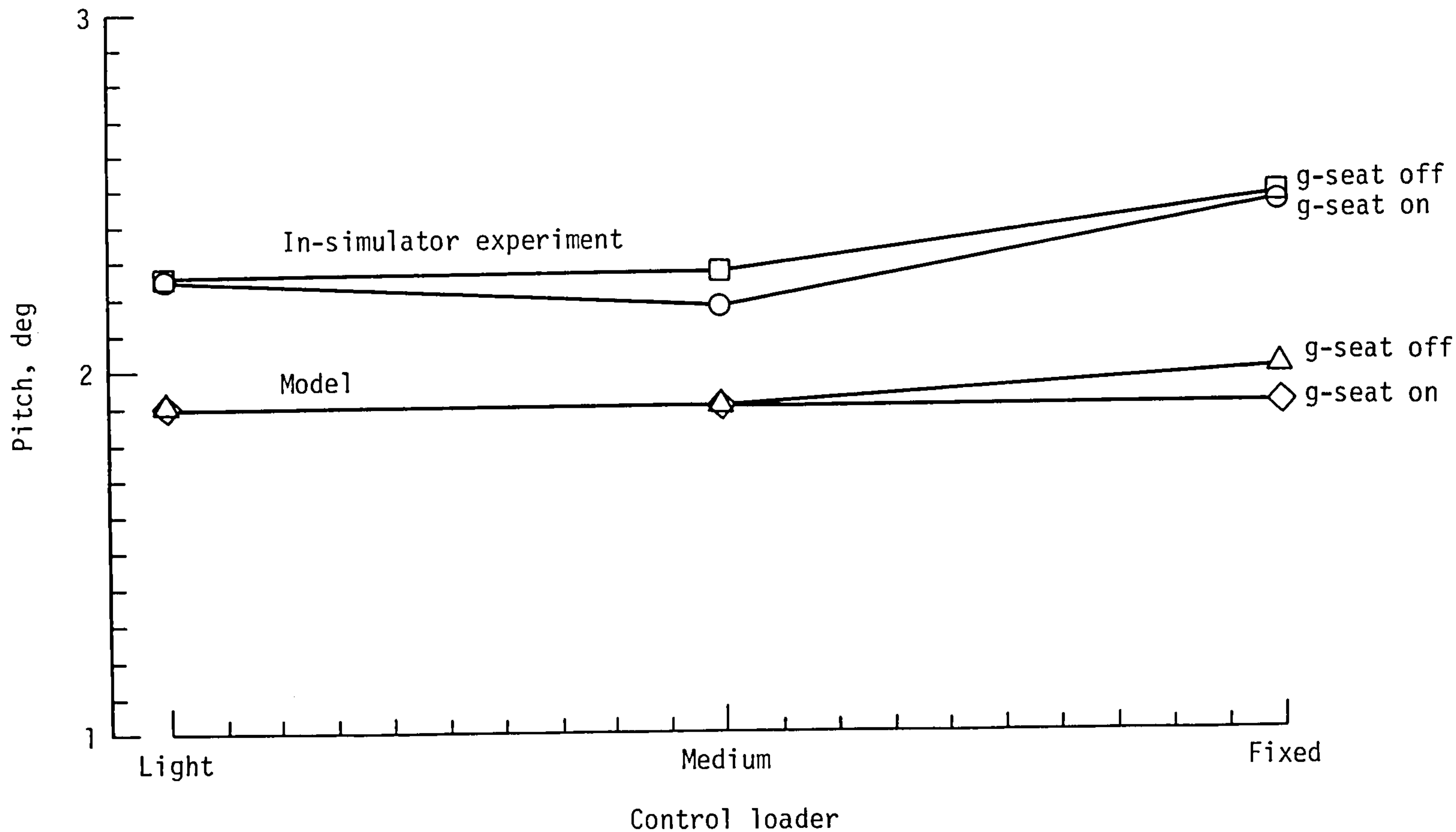
(d) Stick input results for "best" condition.

Figure 7.- Continued.



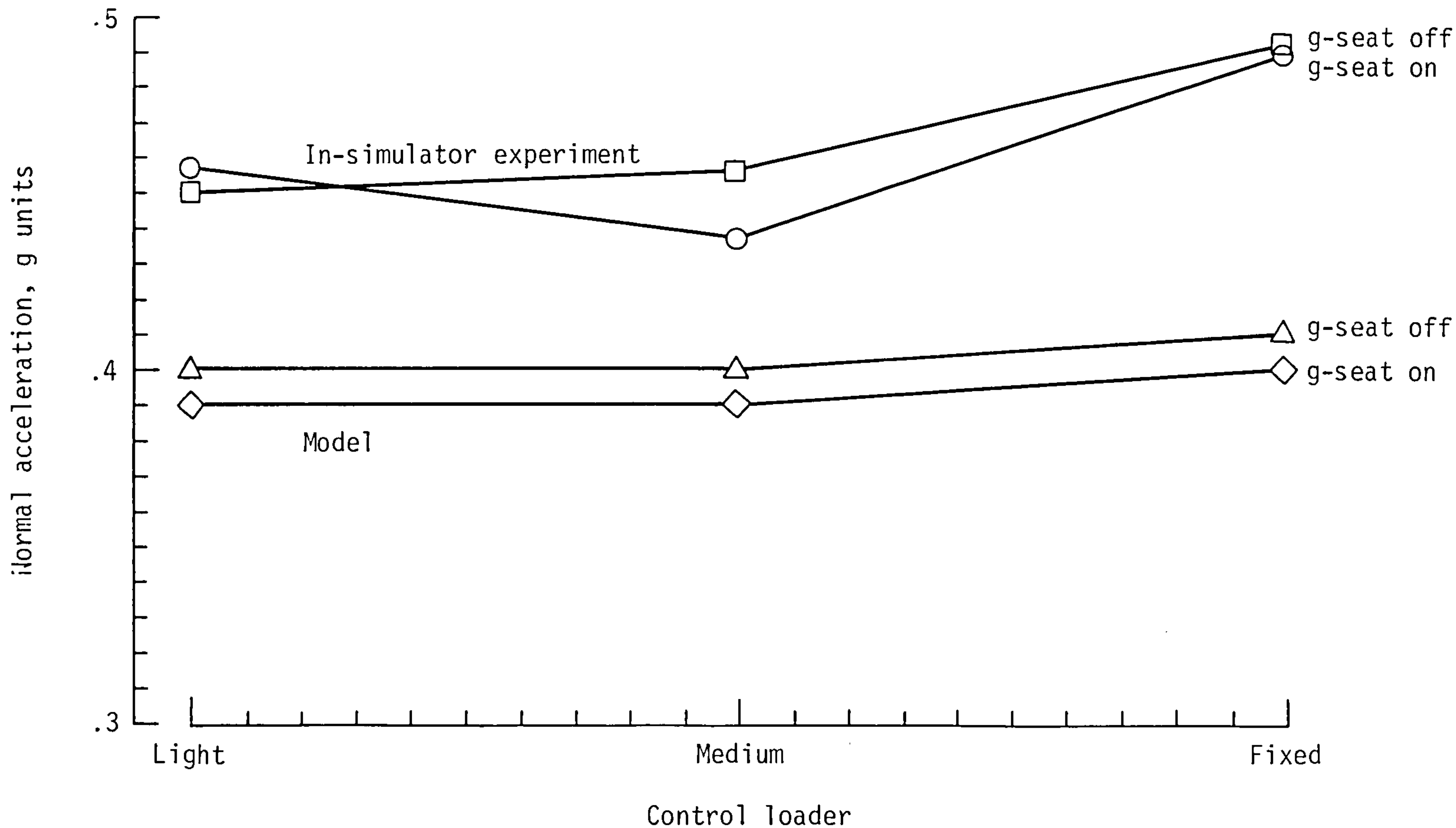
(e) Vertical-tracking-error results for "worst" condition.

Figure 7.- Continued.



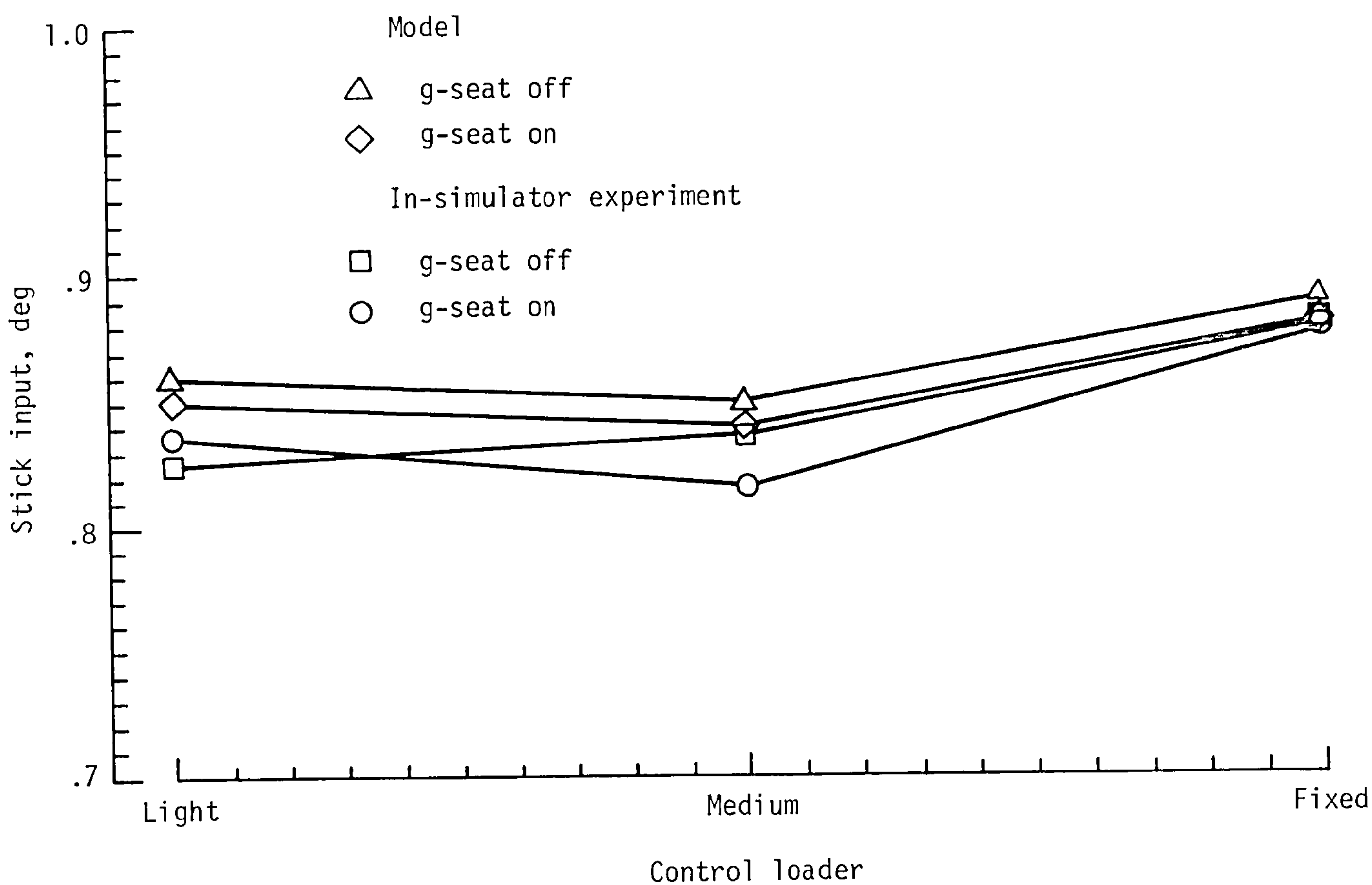
(f) Pitch results for "worst" condition.

Figure 7.- Continued.



(g) Normal acceleration results for "worst" condition.

Figure 7.- Continued.



(h) Stick input results for "worst" condition.

Figure 7.- Concluded.

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16. Abstract

A full-factorial in-simulator experiment of a single-axis, multiloop, compensatory-pitch tracking task is described. The experiment was conducted to provide data to validate extensions to an analytic, closed-loop model of a real-time digital simulation facility. The results of the experiment encompassing various simulation fidelity factors, such as visual delay, digital integration algorithms, computer iteration rates, control-loading bandwidths and proprioceptive cues, and g-seat kinesthetic cues, are compared with predictions obtained from the analytic model incorporating an optimal control model of the human pilot. The in-simulator results demonstrate more sensitivity to the g-seat and to the control-loader conditions than were predicted by the model. However, the model predictions are generally upheld, although the predicted magnitudes of the states and of the error terms are sometimes off considerably. Of particular concern is the large sensitivity difference for one control-loader condition, as well as the model/in-simulator mismatch in the magnitude of the plant states when the other states match.

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