Effects of Control Stick Parameters on Human Controller Response

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Abstract

Much interest has arisen on the comparison of the effects of force versus displacement sticks on pilot tracking ability. To investigate this effect, a fixed base laboratory tracking study was conducted to determine the effects of stick displacement and stick force characteristics on human tracking performance. Three different levels of control stick force/displacement characteristics and stick electrical gain were varied to observe their influence on RMS (Root Mean Square) tracking error and RMS control activity (stick output).

The results of this study indicated that both RMS tracking error and RMS control activity were influenced by the three different levels of control stick force/displacement characteristics and stick electrical gain. One method of investigating human controller response is to study the empirical data obtained from this experiment and to compare it to the Optimal Control Pilot Model (OCPM) which represents standard forms of human response. Fitting the Optimal Control Pilot Model to these data showed that the effect of changing electrical control gain markedly changed the motor time constant parameter of the OCPM. In model fitting these data for changes in the force/displacement characteristics of the stick, the time delay parameter of the OCPM had to be changed significantly so that the empirical data would match the model. In summary, this paper reports that the human neuromotor time constant was affected by the electrical control gain of the stick while the spring stiffness of the stick influenced the time delay characteristics of the human response behavior.

Introduction

Direct control of translational modes is being designed into certain high-performance fighter aircraft to enhance maneuverability in air-to-air combat situations. The ability of the pilot to control such a vehicle is affected by the presence of biomechanical feedback between the airframe and the control stick [1]*. For example, if the pilot commands lateral translation (i.e., side force), the aircraft will accelerate in the commanded direction, but the inertia of the arm/hand/stick system will act on the stick to partially cancel out the intended input. Laboratory studies suggest that such biomechanical coupling will tend to degrade performance in an air-to-air tracking task (Korn and Kleinman, [2]).

The Air Force has conducted studies to develop methodologies for

* A more detailed version of this paper can be found in reference [1].

the optimal design of control sticks in high-acceleration environments. While near-optimal tracking performance can usually be obtained for a wide range of stick parameters in a fixed-base tracking task, the presence of biomechanical coupling can appreciably narrow this range when the task is performed in a high-acceleration environment (Korn and Kleinman [2]). Some initial work has been done to develop a design methodology using the combination of a pilot/vehicle performance model and a model for biomechanical coupling (Levison and Houck [3], Jex and Magdaleno [4], Levison, [5]).

Levison and Houck [3] used the optimal control model (OCM) for pilot/vehicle systems as the basis for their combined model, and they suggested that control-stick characteristics be accounted for partly by the structure of the quadratic performance criterion used in obtaining a model solution, and partly by the introduction of a second-order dynamical submodel to represent the pilot/stick interface. They also recommended that further studies be undertaken to refine and validate the aspects of the OCM related to motor limitations.

The purpose of the study discussed herein was to provide a detailed look at the pilot/stick interface as suggested in Levison and Houck [3]. A fixed base laboratory study was conducted with the major experimental variables being stick force/displacement characteristics and electrical control gain. Both parameters were varied over a sufficiently wide range to exceed optimality.

Description of The Experiment

Nine test subjects ranging in age from 24 to 39 years participated in a fixed-base laboratory experiment involving tracking. Laterally-directed control forces resulted in lateral movement of a cursor displayed electronically in an inside-out format. Tracking dynamics were pure rate control (K/s) plus an effective time delay of 80 msec induced by the simulation and display apparatus. A sum-of-sines forcing function was designed to simulate a first-order noise process having a break frequency at 4 rad/sec. The forcing function was treated as a vehicle disturbance and was injected in parallel with the operator's control input. Additional experimental details may be found in Repperger, et al., [6].

The principle experimental variables were control stick mechanical characteristics (i.e. force/displacement relationship) and electrical gain. Three mechanical configurations were explored: a nearly isometric "force stick", a "strong displacement stick" having significant displacement and a modest force restraint, and "weak displacement stick" having significant displacement and a relatively small force restraint.

Three electrical gains were explored for each stick configuration. A mid-range gain was selected to lie within the optimal gain range; a gain approximately one tenth the optimal gain was selected to require substantial control forces and/or displacements; and a gain approximately nine times the optimal gain was selected to explore effects of motor-related limitations such as tremor.

Table 1 shows the force/displacement characteristics and electromechanical gains of the nine control-stick configurations. The force/displacment ratio was essentially infinite for the force stick, .071 pounds/ degree for the strong displacement stick, and about .014 pounds/ degree for the weak displacement stick.

The fourth and fifth columns of Table 1 show the electrical control gains in terms of volts of effective control input per mechanical unit (pounds force or degrees displacement). Control requirements on the part of the pilot, however, are best seen from the last two columns, which show the amount of physical activity required to generate 1 volt of control input - approximately the average force level generated by the test subjects in the experimental study. Force requirements range from about 0.2 to 15 pounds for the force stick configurations. Required forces decrease by nearly an order of magnitude for the strong displacement stick and by another factor of 5-6 for the weak displacement sticks. Displacement requirements for both displacement sticks range from about 0.3 to about 25 degrees per volt control input.

Table 1 - Control Stick Characteristics

Configuration		Mechanical and Electrical Characteristics				
Stick	Gain	Force/Disp.	Volt/Lb.	Volt/ Deg.	Lb/Volt	Deg/Volt
	Low		.0673		14.9	
Force	Mid	∞	.797	—	1.25	—
	High		4.24		0.236	
	Low		0.572	.0403	1.75	24.8
Strong	Mid	0.0714	5.18	.375	0.193	2.67
Disp.	High		46.6	3.37	0.022	0.297
	Low		2.87	0.0403	.348	24.8
Weak	Mid	0.0138	27.3	.374	.037	2.60
Disp.	High		246.	3.37	.004	.297

Experimental Results

Performance Scores

Standard deviation (SD) scores were computed from time histories of the tracking error and of the pilot's control input. These scores were computed first from individual time histories, and then averaged across replications to obtain mean SD scores for each subject, each condition. These within-pilot average scores were then averaged across pilots to yield population means and an across-subject standard deviations of the SD scores for each experimental condition. These statistics were then subjected to paired-difference t-tests to determine the statistical significance of changes in mean performance resulting from changes in experimental conditions. A test on outliers was performed jointly on two variables (the error and control SD scores.). A value of L=3.0 standard deviations was selected to reflect (cf. Levison and Muralidharan [7]) a 1% probability criterion of a trial being outside the normal population. Thirteen outliers were identified out of a data base of 243 experimental trials.

The effects of stick configuration on error and control SD scores are illustrated in figure (1). Response variables are shown in physiological units; error scores in degrees visual arc, and control scores in both pounds force and degrees displacement. Figure (1a) illustrates that slightly lower error scores were obtained for the force stick than for either of the displacement sticks for the mid-range (baseline) electrical gains. Low control gain degraded performance of the force stick configuration, whereas high gain degraded performance for both displacement-stick configurations.
Figure (1b) shows that control force scores varied by almost two orders of magnitude with electrical gain for a given manipulator, and by over three orders of magnitude across the entire experiment. Because of this large variation, control SD scores have been plotted on a logarithmic scale.

As anticipated, control effort (force and displacement) varied inversely with electrical gain. Control forces decreased with decreasing force/displacement ratios. Control displacements, however, were similar for both displacement sticks.

Paired-difference t-tests were performed on the SD scores to indicate the statistical significance of performance changes with changes in force/displacment characteristics and electrical gain. Table 2a shows the alpha significance levels obtained by comparing pairs of electrical gains for each control stick; Table 2b shows the results of comparing control sticks for each relative gain level. Differences yielding an alpha level of .05 or less are considered "significant" in the ensuing discussion. The following trends were observed:

1. Control scores consistently increased with electrical gain.
2. For each control stick, minimum (or near-minimum) tracking error was achieved with the mid-range mechanical gain.
3. Force/displacement characteristics had less of an influence on performance then the electrical control gain.

<u>Frequency Response</u>

Analysis procedures followed in previous laboratory tracking studies (Levison, [8]) were employed to compute estimates of the linear portion of the pilot's response strategy (gain and phase shift) as well as estimates of the stochastic portion ("pilot remnant"). The sum-of-sines type of input used in the experiments facilitated decomposition of the tracking error and the pilot's control response into input-correlated and remnant-related components. Comparison of input-correlated spectral estimates with estimates of remnant at neighboring frequencies provided a means for determining the reliability of the describing function measurements. A gain or phase

TABLE 2.* RESULTS OF PAIRED-DIFFERENCE T-TESTS ON SD SCORES

a) Effects of Electrical Gain

Basis for Comparison

	Force			Strong Disp.			Weak Disp.		
VARIABLE	LOW, MID	HIGH, MID	HIGH, LOW	LOW, MID	HIGH, MID	HIGH, LOW	LOW, MID	HIGH, MID	HIGH, LOW
ERROR	.001	--	.001	--	.01	.02	--	.01	.01
Err. rate	.01	.01	.001	.02	.001	.001	.01	.05	.02
CONTROL	.001	.01	.001	.02	.001	.001	.01	.01	.01
Ctr. rate	.01	.001	.001	.01	.001	.001	.01	.001	.001

b) Effects of Force/Displacement Characteristics

Basis for Comparison

	Low Gain			Mid Gain			High Gain		
VARIABLE	FS SDS	FS, WDS	SDS WDS	FS, SDS	FS, WDS	SDS, WDS	FS, SDS	FS, WDS,	SDS, WDS
Error	--	--	--	.02	.01	--	.001	.01	--
Err. rate	.02	.01	.05	--	.02	--	.001	.05	--
Control	.05	.01	--	--	--	--	.001	.01	--
Ctr. rate	.01	.01	--	--	.02	--	.001	.01	--

Entries show alpha levels of significance.
Dash indicates alpha greater than 0.05.

* From Reference [1]

measurement was considered valid at a given frequency only if the input-correlated power was at least 6 db greater than the corresponding average remnant power for both the error and control signals.

The effects of electrical control gain on frequency response measures are shown in figure 2 for the three mechanical stick configurations. Figure 3 shows the effects of force/displacement characteristics on frequency response, with the electrical gain at the mid (and presumable near-optimal) level for each configuration. For all figures, 0 db gain represents one control/volt/degree tracking error and 0 db remnant represents a power density of 1 volt^2 per radian/second.

Overall, increasing the control gain from the smallest to greatest values results in significant increases in pilot gain and remnant, and small decreases in phase lag. These effects differed in detail, however, across the stick configurations. Taking the mid control gain as a reference condition, Figure 2 shows that a decrease in control gain resulted in a substantial decrease in pilot gain at all frequencies, and a decrease in pilot remnant at high frequencies. An increase in control gain produced the opposite trends, but the effects were considerable smaller.

Taking the mid control gain as the reference condition, figures 4 and 5 show that, for the displacement sticks, an <u>increase</u> in control gain produced the greatest effects. The major effect was to increase pilot remnant at all frequencies; small increases in pilot gain were also seen. Smaller effects were obtained when the control gain was lowered with remnant reductions occurring mainly at the higher measurement frequencies.

Figure 3 shows frequency response trends consistent with the trends of the error scores; namely, that tracking response degrades as the restoring spring constant is reduced. Specifically, the largest pilot gain, least phase lag, and least remnant were observed for the force stick; and the lowest gains, greatest phase lags, and greatest remnant were found for the weak displacement stick. In general, these effects were smaller than the differences caused by varying control gain.

Model Analysis

As part of the procedure for developing a predictive model for closed-loop performance, the data presented above were further analyzed in order to identify independent (or "pilot related") parameters of the optimal control model (OCM) for pilot/vehicle systems.

Identification of Pilot Related Parameters

A quasi-Newton gradient search procedure was employed to identify the following five model parameters: (1) Observation noise variance associated with perception of error displacement, (2) Observation noise variance associated with perception of error rate,

(3) Motor noise covariance, (4) Time delay, and (5) Relative "cost" weighting on control-rate variance.

No constraints were placed on these parameters during the search, other than the requirement that they remain positive. The control-rate cost coefficient was converted to an equivalent "motor time constant". The resulting parameters of interest, and their units are defined in table 3:

TABLE 3 - OCM PARAMETERS IDENTIFIED BY THE QUASI-NEWTON PROCEDURE

Pe = Observation Noise/Signal Ratio on Tracking Error, dB
$P\dot{e}$= Observation Noise/Signal Ratio on Error Rate, dB
Pm= Motor Noise/Signal Ratio, dB
Td= Effective Operator Time Delay, seconds
Tm= Motor Time Constant, seconds

Exploration of Alternative Model Parameterization

Alternative model structures were also explored in an attempt to find a set of invariant "pilot related" parameters that would account for the effects of both force/displacement characteristics and electrical control gain.

The independent model parameters identified for each experimental condition are shown in figure 6. The observation noise/signal ratios associated with error and error rate were averaged to provide a composite observation noise/signal ratio. Qualitative tests for statistical significance (discussed in [8,9]) showed that, for all three mechanical stick configurations, the motor time constant was the parameter most significantly influenced by electrical control gain, observation and motor noise/signal ratios collectively were less significantly influenced, and time delay differences were not significant. On the other hand, changes in the stick force/displacement characteristics (for a given relative electrical gain) had a significant influence only on the time delay parameter.

This effort focused on explaining the apparent task-related changes in two parameters: motor time constant, and time delay. The mathematical formulation of the OCM was not modified in this exercise; rather, alternative parameterizations consistent with the existing model framework were explored. The approach adopted by Levison and Houck [3] was pursued: the performance index was modified to include true penalties on control activity, and second-order models were explored for the man/stick interface.

The following four mutually-exclusive hypotheses were tested:
1. The cost coefficient associated with control-rate variance represents a true penalty for generating physical control activity. Thus the data should be explained by a cost function of the following form:

$$J = \sigma^2_e + G\,\sigma^2_{\dot{u}} \qquad (1)$$

2. The cost coefficient associated with control-rate reflects both a response bandwidth limitation and a penalty on rate-of-change of control force.

3. The performance index includes penalties on error, control, and control rate. Thus,

$$J = \sigma^2_e + R\,\sigma^2_u + G\,\sigma^2_{\dot{u}} \qquad (2)$$

4. The performance index includes penalties on error, control, and control rate as before, except the penalty is associated with rms control, not control variance. Thus,

$$J = \sigma^2_e + r\,\sigma_u + G\,\sigma^2_{\dot{u}} \qquad (3)$$

To test the last three hypotheses, a fixed value of Tm was selected on the basis of the original identification, the coefficient relating to physical control activity (G,R, or r) was identified for each of the force stick conditions, the average value for this control-related coefficient was computed, and matching error ratios were identified. To determine matching errors, an average "G" was identified for each of the three stick conditions by the gradient search scheme. Then using a fixed value of G to re-identify the remaining model parameters, new matching errors were computed. These new matching errors were normalized with respect to the original matching errors to provide a measure of the degradation in model-matching capability resulting from the assumption of a fixed penalty on physical control activity.

The matching error ratio (MER) [8,9] provides a qualitative test for significance. That is, if any MER obtained when testing a given hypothesis is greater than some criterion level, we consider the model match to be "significantly" worse than the baseline match (i.e., no constraints on the independent model parameters), and therefore grounds for rejecting the hypothesis. A matching error ratio of 1.4 was selected as the criterion to provide a treatment consistent with similar model applications in previous studies.

Table 4 shows that the simplest hypothesis (consistent penalty on physical control rate) provided the least good match to the data (maximum MER of 3). The most consistent results were obtained with the hypothesis that the human operator is characterized by a fixed motor time constant and a fixed penalty on rms control force. In this case, the MER ranged from less than unity to 1.3 for the three conditions tested. Less consistent results were obtained with the hypothesis that the invariant parameters are motor time constant and penalty on control-force variance, where a maximum MER of 1.7 was obtained.

Table 4 - Tests of Hypotheses Concerning Invariant Control Related Model Parameters

Electrical Control Gain	Hypothesis			
	1	2	3	4
Low	3.0	1.2	1.9	<1
Mid	1.1	1.7	---	1.3
High	3.4	1.3	---	1.1

Summary and Conclusions

A fixed-base laboratory study of mechanical and electrical control-stick parameters yielded the following major results:

1. Effective control input to the plant increased with electrical control gain for the three mechanical sticks explored. This was initially modeled as a change in the time constant.
2. For each mechanical control stick, minimum or near-minimum tracking error was achieved with the mid-range gain.
3. Force/displacement characteristics had less of an influence on performance than did the control gain. These effects were modeled largely by changes in effective time delay.
4. The quadratic performance index was revised by including a penalty on RMS control activity. A greater degree of parameter invariance was obtained from the modeling.
5. Attempts to find an invariant set of model parameters to account for mechanical stick parameters were unsuccessful. A second-order mass spring/damper submodel for the pilot/stick interface was explored, but a reasonable selection of parameters yielded effects that were substantially greater than those found experimentally. The notion of a second-order stick interface submodel need not be ruled out. The parameterization of such a model, however, should take account of the pilot's active control over his effective spring constant and damping characteristics; measurement of such parameters in a strictly passive setting are likely to be inadequate.

References

[1] Levison, W.H., "Effects of Control Stick Parameters on Human Controller Response", Report No. 5510, Bolt, Beranek, and Newman, Inc., January, 1984.

[2] Korn, J. and Kleinman, D.L., "Modeling Lateral Acceleration Effects on Pilot Performance", Proc. of The Sixteenth Annual Conference on Manual Control, Cambridge, MA, pp. 340-349, May, 1980.

[3] Levison, W.H., and Houck, P.D., "Guide For The Design of Control Sticks in Vibration Environments", AMRL-TR-74-127, February, 1975.

[4] Jex, H.R., and Magdaleno, R.E., "Biomechanical Models For Vibration Feedthrough To Hands and Head For a Semisupine Pilot", Aviation Space and Environmental Medicine, vol. 49, No. 1, pp. 304-317, January, 1978.

[5] Levison, W.H., "Model For Human Controller Performance in Vibration Environment", Aviation Space and Environmental Medicine, vol. 49, No. 1, pp. 321-327, January, 1978.

[6] Repperger, D. W., Levison, W.H., Skowronski V., O'Lear, B., Frazier, J.W., and Hudson, K.E., "Stick Controller Design For Lateral Acceleration Environments", Proc. of The Eighteenth Annual Conference on Manual Control, Dayton, Ohio, June, 1982, pp. 427-440.

[7] Levison, W.H. and Muralidraran, R., "Analysis of Manual Control Tasks in Support of The Chemical Defense Program", Report No. 5168, Bolt, Beranek, and Newman, Inc., Cambridge, MA, November, 1982.

[8] Levison, W.H., "The Effects of Display Gain and Signal Bandwidth on Human Controller Remnant", AMRL-TR-70-93, March, 1981.
[9] Levison, W.H., "A Quasi-Newton Procedure for Identifying Pilot-Related Parameters of the Optimal Control Model", Proc. of the Seventeenth Annual Conf. on Manual Control, Los Angeles, CA, June, 1981.

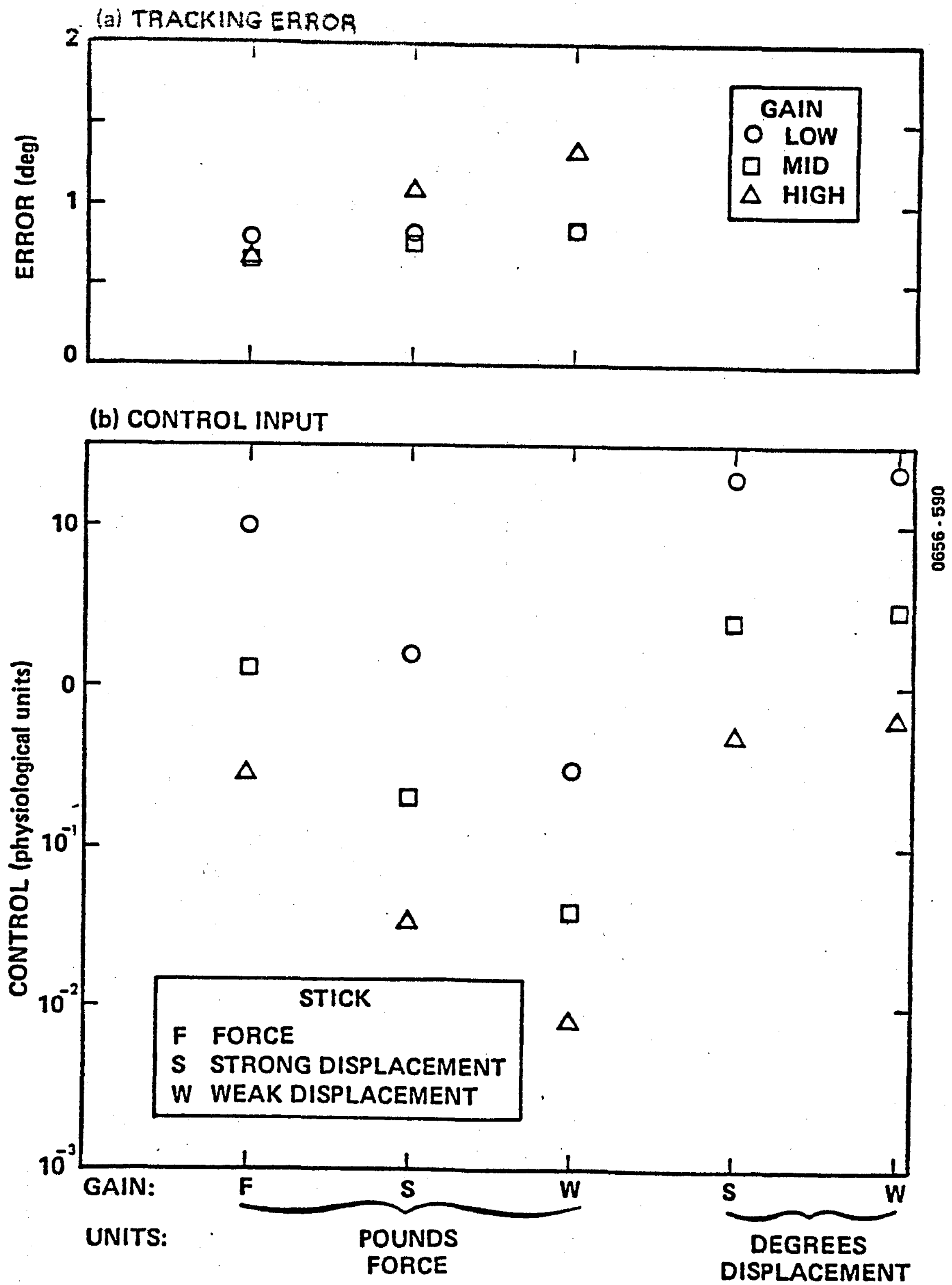

Figure 1.* Effects of Stick Configuration on SD Performance Scores, Physiological Units

Average of 9 subjects, 3 trials/subject.

* From Reference 1

a) Force Stick

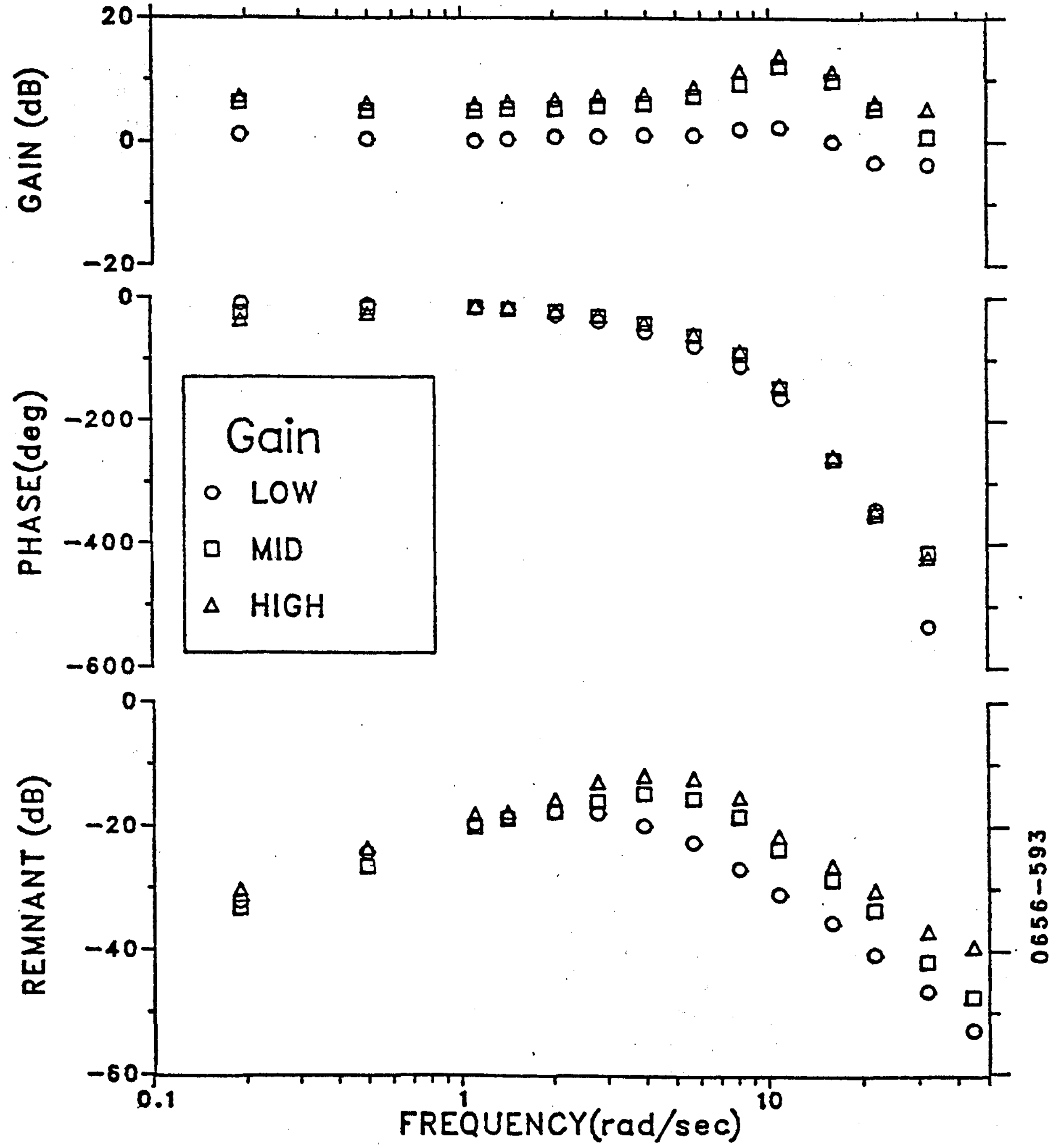

Figure 2.* Effects of Electrical Control Gain on Frequency Response

Average of 9 subjects, 3 trials/subject

* From Reference 1

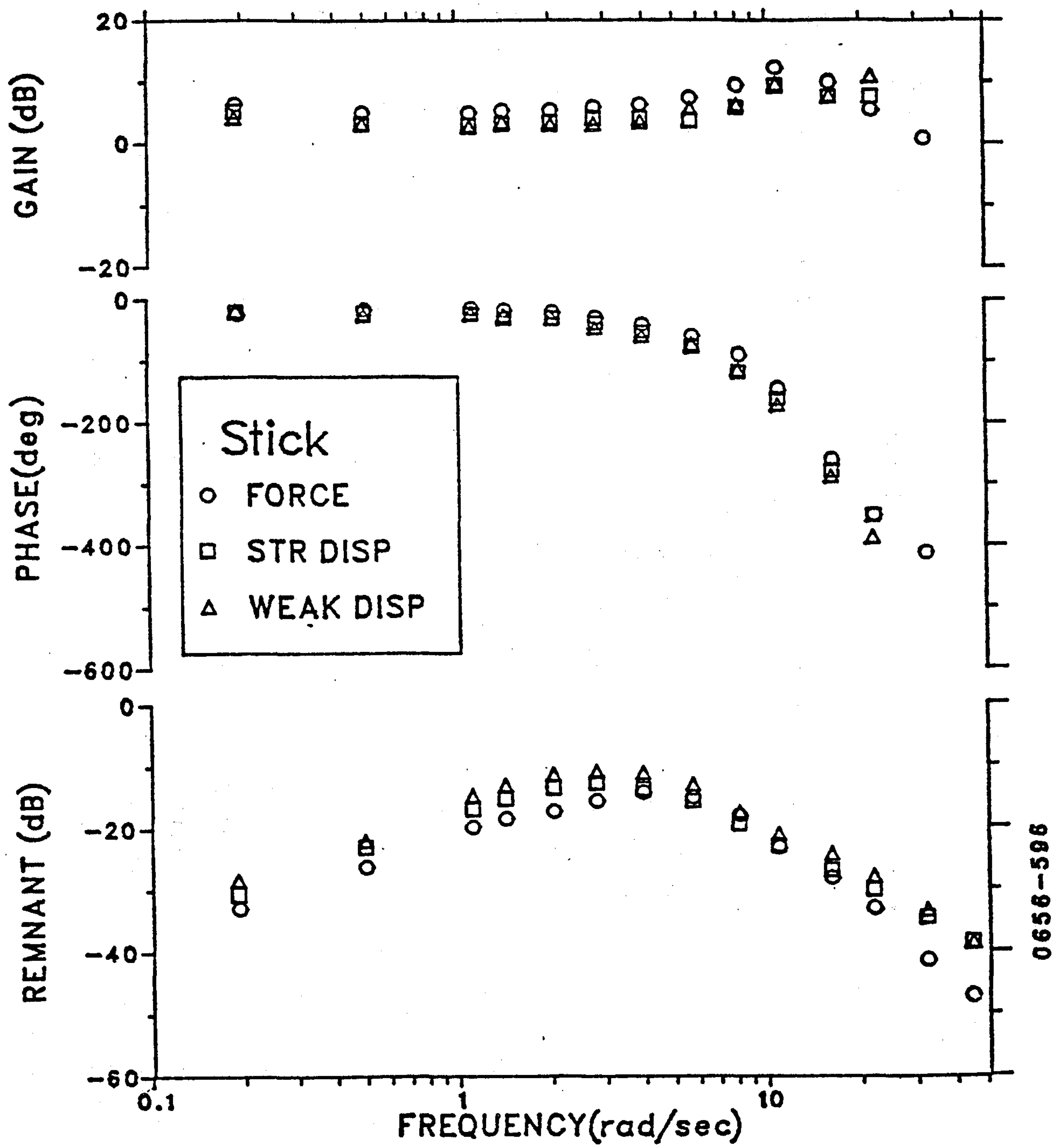

Figure 3 *. Effects of Force/Displacement Characteristics on Frequency Response

Mid Gain.
Average of 9 subjects, 3 trials/subject.

* From Reference 1

b) Strong Displacement Stick

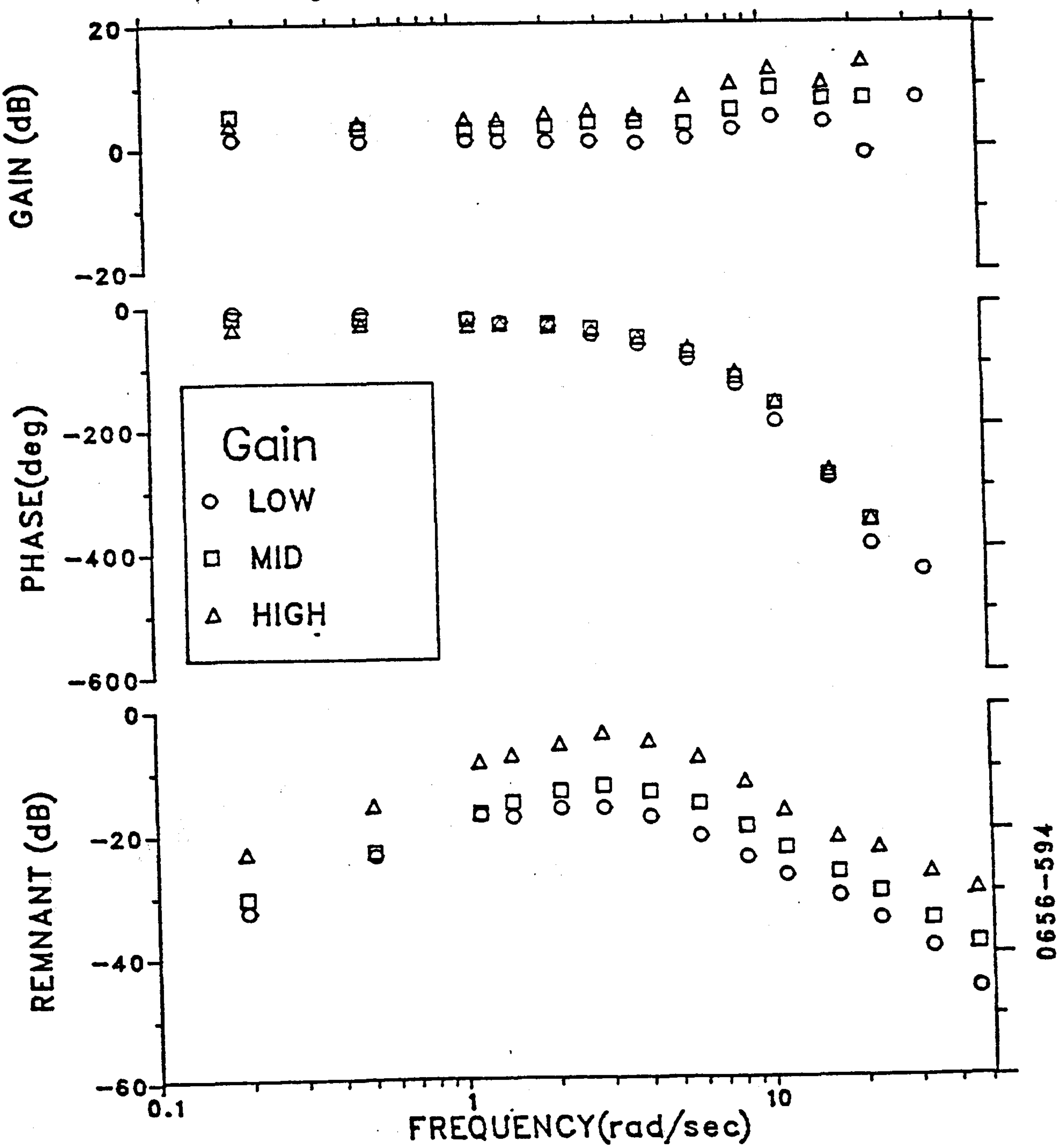

Figure 4.*

* From Reference 1

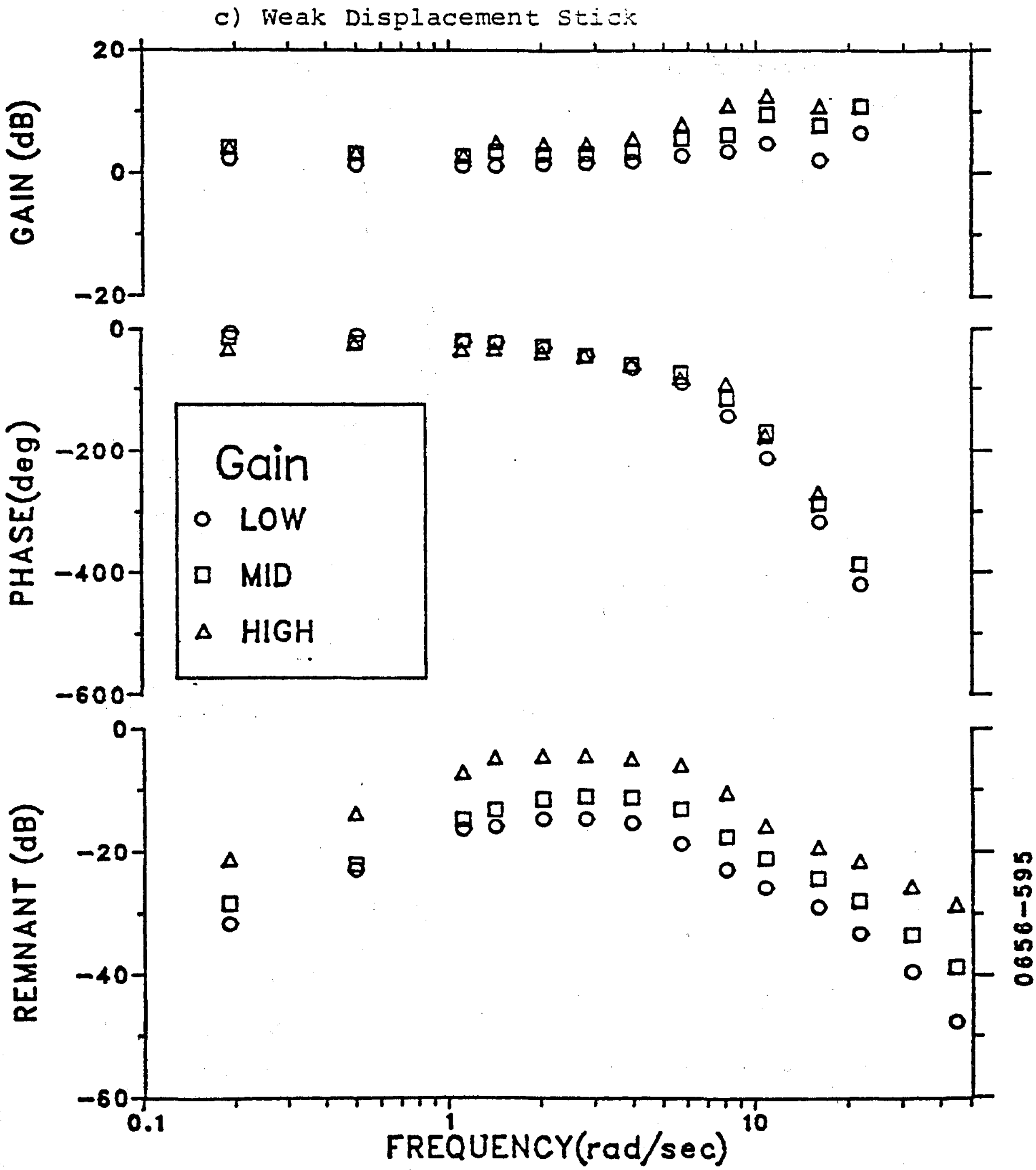

Figure 5.*

* From Reference 1

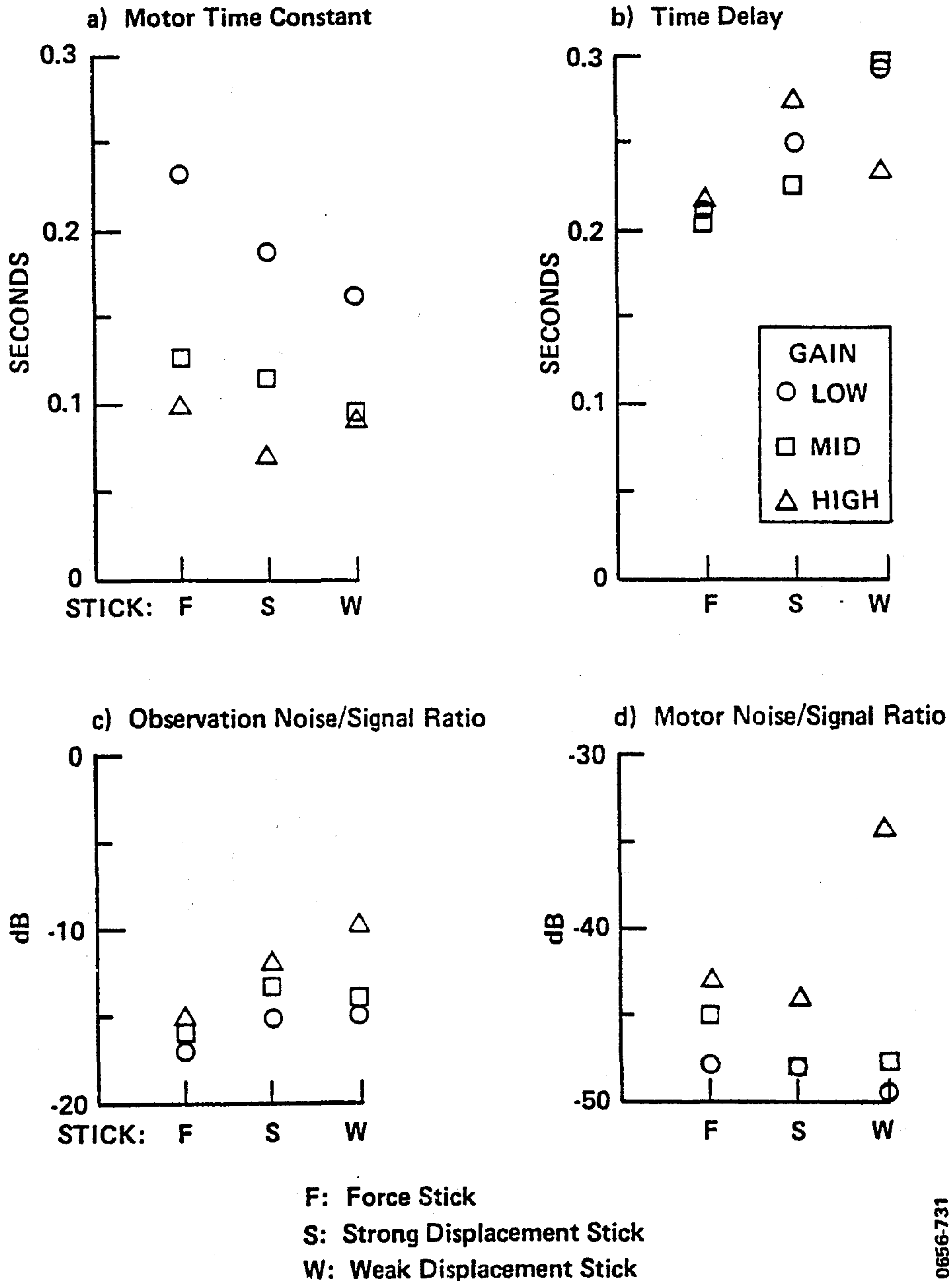

FIG. 6.* EFFECTS OF STICK CONFIGURATION ON MODEL PARAMETERS

* From Reference 1