Flight-Control Studies in the Small Stick Deflection Area

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The relative effects of control-system friction, preload, backlash, gearing, force gradient, damping, and trim rate on handling qualities in the small stick deflection area are investigated. The nonlinear variables of friction, preload, and backlash are given the most attention. A fixed-base, analog-computer flight simulation, with provisions for varying the control-system properties of interest in a carefully defined manner, is used for the investigation. Scoring is accomplished by direct quantitative measurements, in addition to pilot Cooper Rating, and a unique performance-measurement parameter (*g*-ft-lb) is developed. It is concluded that friction is the most important control-system property in the small stick deflection range of flying.

Introduction

MUCH flight simulation has been accomplished in which the nonlinear aspects of friction, preload, and backlash in the control system have been omitted or considered negligible. This procedure is commendable in that it reduces the total number of variables to be considered and, in particular, eliminates variables that are difficult to manage. For example, it is difficult, if not impossible, to use Laplace transform techniques to describe a system involving nonlinear functions. Within the context of mechanical control systems, however, it is evident that these inherent properties of friction, preload, and backlash cannot be completely neglected with respect to their effect on handling qualities. This is recognized, of course, in Military Specification MIL-F-8785, in which maximum allowable breakout forces for the airplane under consideration are specified. MIL-F-8785 also has qualitative statements concerning the desirability of linear response, positive centering, minimum backlash, etc., but the establishment of specific value criteria have, probably wisely, not been given. Nevertheless, the flight-control system designer requires better understanding of the significance of these nonlinear properties and their relationship with associated functions. This paper is a report of a program designed to help fill this need—through flight simulation and without the commitments of flight test or full-scale system duplication.

Development of the Flight Simulation

The basic "vehicle" used to perform the flight simulation is composed of several elements and is shown in block diagram form in Fig. 1.

Although the control-system dynamics element was the only element investigated, all the elements are necessary to conduct the investigation. In addition, the particular variables of interest within the control-system dynamics element have profound significance on the choice and character of the supporting elements. These supporting elements, i.e., the task, the airplane dynamics, the visual cues, etc., must be carefully developed to provide the proper background and environment for illumination and investigation of the variables of interest.

Development of the Supporting Elements

Airplane dynamics

The values for the significant parameters of this element were selected to make the nonlinear properties, such as friction, critical, and otherwise, present optimum handling qualities. Although choice was partially restricted by the specific airplane then under investigation, the significant parameter values that were used are listed.

Stabilizer degrees per g	=	0.5
Short-period natural frequency	=	0.58 cps
Short-period damping ratio	=	0.5

Note that these values of frequency and damping are reasonably close to the "thumbprint" optimum and thus offered minimum interference to evaluation of the nonlinear variables on handling qualities.[1] These parameter values corresponded to the airplane flight condition of Mach 0.6 at sea level.

Task

In what pilot tasks could we expect the properties of friction, preload, and backlash to be the most significant? It seemed reasonable that tracking tasks involving small stick deflections around neutral would exhibit the greatest effect, and these were therefore selected. It was also postulated that the major portion of all flying time is spent in this small stick deflection area and thus deserves consideration in any handling-quality evaluation; hence, the title of this paper.

This reasoning, plus scoring considerations, eventually led to the selection of three tasks, which are described here.

Task A: Stabilize the airplane in straight and level flight at the flight condition. Press the "event" button and fly a time-altitude schedule (as shown in Fig. 2) as closely as possible, with no control inputs other than stick deflections. Note: A special timer-clock was provided on the instrument panel for the pilot on this task, and it is shown in Fig. 3. The "event" button was a switch on the left side of the cockpit which established time zero for each task at the pilot's discretion. The timer-clock was started by the "event" button.

Task B: Stabilize the airplane in a 3000 ft/min descent at some altitude appreciably above 500 ft. When the altitude reaches 500 ft, press the event button and fly the airplane

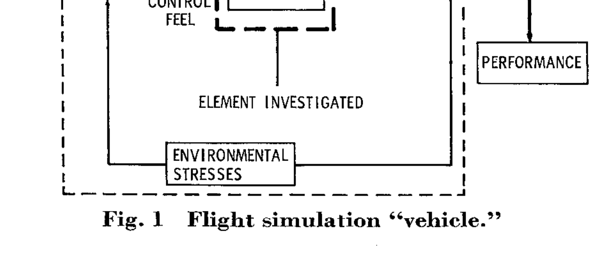

Fig. 1 Flight simulation "vehicle."

Presented at the AIAA Simulation for Aerospace Flight Conference, Columbus, Ohio, August 26–28, 1963 (no preprint number; published in bound volume of preprints of the meeting); revision received March 16, 1964.

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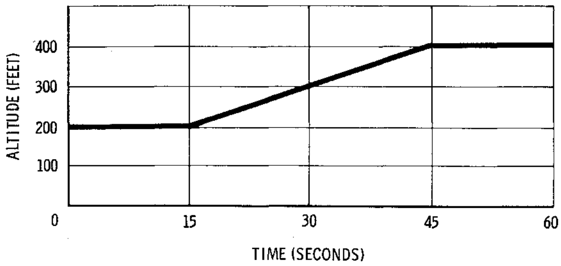

Fig. 2 Task A altitude-time (ramp) problem.

to the command bar on the attitude indicator for 60 sec. Note: The command bar position was programed so that, if it were maintained coincident with the airplane representation on the attitude indicator, the airplane would develop a normal acceleration time plot, as shown in Fig. 4.

Task C: Stabilize the airplane in straight and level flight. Press the event button and endeavor to maintain constant altitude and zero stick force with the control stick and trim button for 60 sec. Note: When the "event" button was pushed, the computer was programed to introduce series mistrim, as shown in Fig. 5. The "airplane" was equipped with parallel trim. The trim button was a conventional four-way switch located on the stick grip.

Other Supporting Elements

Without a breakdown into the specific elements, the remainder of the environment is described briefly as follows.

A fixed-base full-scale cockpit with conventional stick and rudder controls and provisions for closing the canopy for Instrument Flight Rules simulation, is shown in Fig. 6.

The instrument panel, with the special timer-clock installed, is shown in Fig. 7.

Instrument responses in terms of damping, time lags, and stability were carefully monitored to insure performance as nearly airplane-equivalent as possible and to prevent spurious visual cues.

A random gust environment with a root-mean-square value of 2.7 fps was superimposed on the airplane dynamics. This was considered a reasonable "average" value for the gusts that could be expected at sea level.[2]

An attempt was made to provide the environmental stresses element with a device called a g seat. In general, this device applied an "up" force to the pilot's seat proportional to, and in phase with, positive airplane g's. The success in providing realistic cues with the device was controversial.

The total simulation was limited to three degrees of freedom (pitch axis only), although the stick could be moved laterally against a simple spring. The airplane dynamics were provided by general purpose PACE analog computer equipment.

Control-System Dynamics Element

The heart of this element, which contained the variables to be investigated, was a closed-loop electro-hydraulic servosystem. A block diagram of this system is shown in Fig. 8.

Basically, this system took the force signal from the force transducer on the stick to the analog-computer model. The

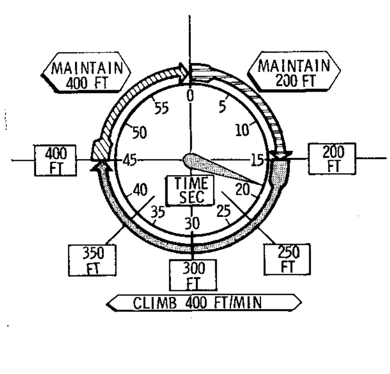

Fig. 3 Special timer-clock for timer clock reference.

analog model computed the commanded stick position and sent it to a high-response hydraulic servo that positioned the stick. Thus, the desired stick force/stick deflection relationships were obtained and could readily be varied in a controlled manner by changing the computer model.

Figure 9 illustrates how the variables of interest were defined. Figure 10 illustrates a typical example of the complete stick force/stick displacement hysteresis loop for a preload value of 1.5 lb, a friction value of 1.0 lb, and a system force gradient of 34 lb/in.

The dotted line in Fig. 10 is the prescribed function, and the solid line is the stick force/stick deflection function actually attained by the hydraulic servosystem. Comparisons between the actual and the prescribed were made before each run. The preload gradient selected is an approximation of the stick displacement vs stick force resulting when the resisting force is separated from the stick by a considerable length of cable and pushrods involving stretch and backlash. System friction was considered to be combined at the stick. A linear relationship and perfect response (zero time constant) was maintained for the stick-deflection vs surface-deflection functions. The ratio of surface deflection to stick deflection (gearing) was coordinated with changes in the system force gradient to maintain 6 lb/g stick force.

Data Taking

The data recorded with each test condition varied slightly with the task but, in general, included the following:

1) E_h vs prescribed altitude-time schedule, where E_h was the departure in feet of altitude from the prescribed schedule

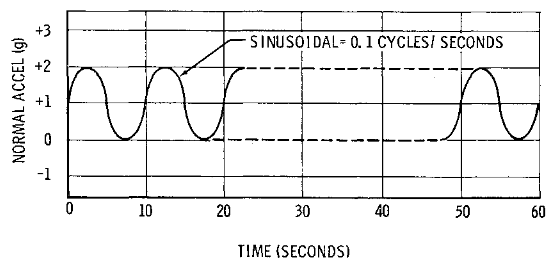

Fig. 4 Task B acceleration-time (roller-coaster) maneuver.

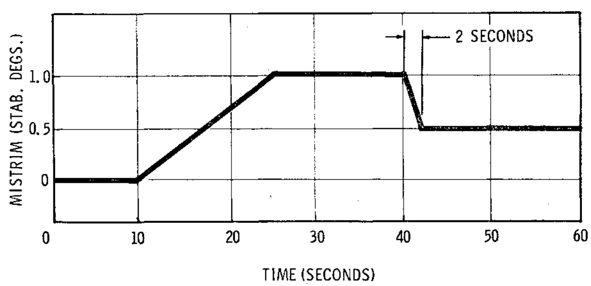

Fig. 5 Task C trim exercise.

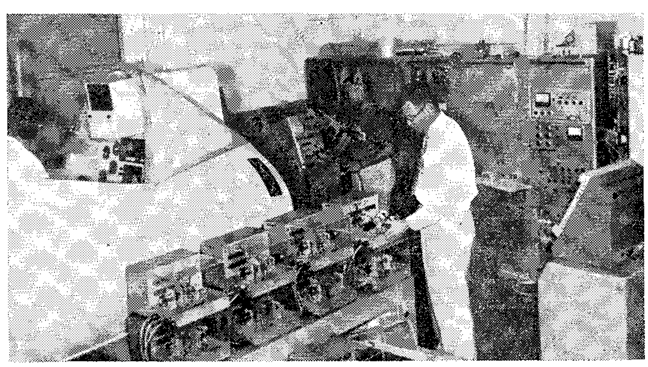

Fig. 6 Simulator cockpit and supporting equipment.

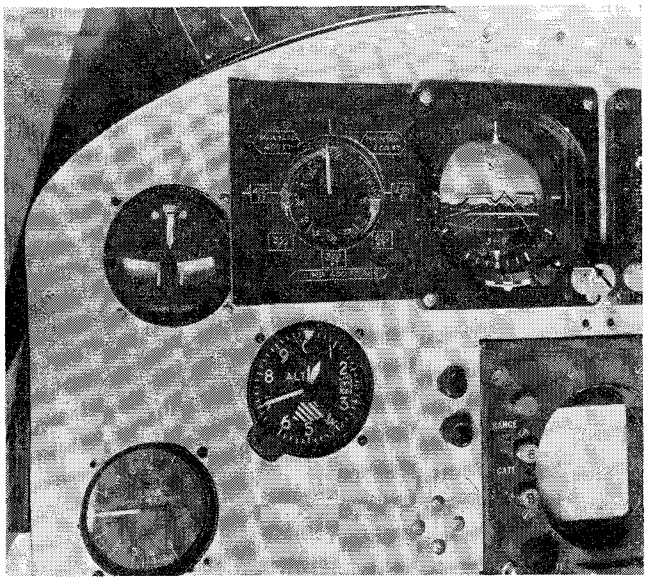

Fig. 7 Simulator cockpit instrument panel.

and is superimposed on the altitude-time schedule plot. Figure 11 illustrates the actual method of recording for Task A.

2) $\int_0^t (|E_h|dt/60)$ vs time, where $|E_h|$ was the absolute value of the departure in feet of altitude from the prescribed schedule during the time interval t.

3) $\int_0^t (|\Delta n_z|dt/60)$ vs time, where $|\Delta n_z|$ was the absolute value of the deviation from 1 g or the prescribed g schedule during the time interval t.

4) $\int_0^t |F_s|dt/60)$ vs time, where $|F_s|$ was the absolute value of the stick force during the time interval t.

5) E_t vs prescribed trim-time schedule, where E_t is the error between pilot's trim setting and that required to maintain the trim-time schedule. E_t was superimposed on the trim-time plot similarly as the one illustrated in Fig. 11 (Task C only).

6) $\int_0^t (|E_{Fs}|dt/60)$ vs time, where E_{Fs} was an arbitrarily defined stick force error from an ideal smooth curve. The error was obtained by operating on total stick force with a washout filter whose time constant was 1 sec (Task B only).

All readings were taken with the time interval t as 60 sec to obtain average values of $|E_h|$, $|\Delta n_z|$, $|F_s|$, etc. for that interval.

Log sheets were kept which recorded the pilot's name, run number, condition number, Cooper Rating, pilot's comments, and the appropriate performance scores; i.e.,

$$\int_0^t \frac{|E_h|dt}{60} \qquad \int_0^t \frac{|\Delta n_z|dt}{60} \qquad \int_0^t \frac{|F_s|dt}{60}$$

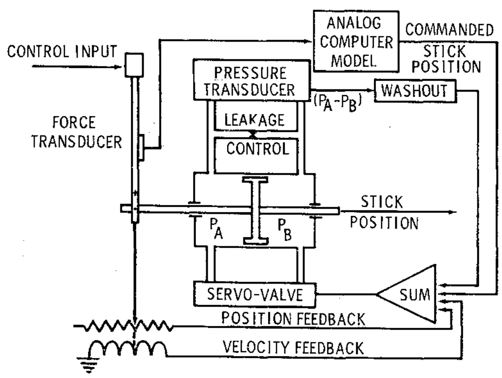

Fig. 8 Electrohydraulic force-displacement system.

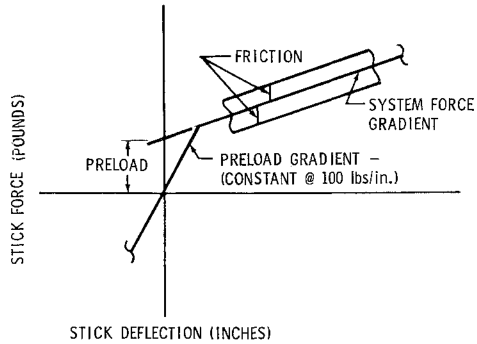

Fig. 9 Definition of the test variables.

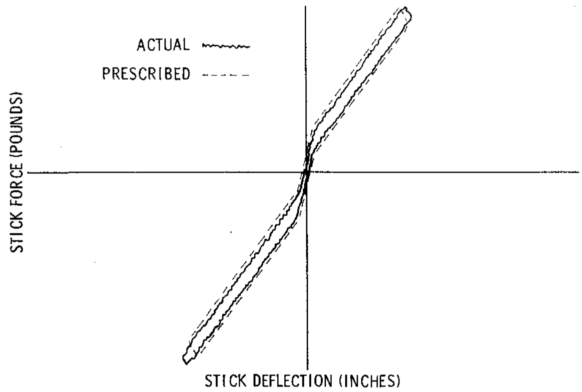

Fig. 10 A test condition, prescribed and actual.

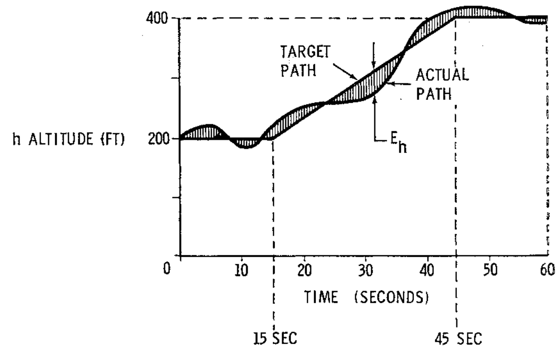

Fig. 11 Altitude error data recording.

Each test condition was run three times and in most cases by more than one pilot.

Five pilots participated in the testing. Each pilot was briefed on the task to be performed before first performing it. Each pilot was instructed to give a rating after each run in accordance with the standard Cooper Rating chart, along with pertinent comments.[3]

The pilot's "learning curves" were associated primarily with the initial performance of each new task. The learning curve effect on the scoring was removed, as far as it was practical, by "flying" a number of trial runs before any data were taken. The trial runs were observed and noted when performance leveled off. Each test was repeated three times, and the resulting scores averaged to reduce further the learning curve and random effects.

Test Results

At the beginning of the program (Task A), the only scoring parameters used were the integrals

$$\int_0^{60} \frac{|E_h|dt}{60} \qquad \int_0^{60} \frac{|\Delta n_z|dt}{60}$$

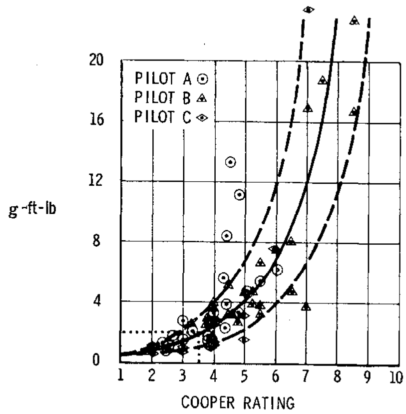

Fig. 12 The *g*-ft-lb vs Cooper rating plot (Task A).

It was reasoned that the error index (average $|E_h|$) furnished by the first integral, plus the smoothness by which the error was minimized (average $|\Delta n_z|$) represented by the second integral, could be used to develop a good total performance measurement. It was further reasoned, and this appears naïve in hindsight, that task performance, as measured by these parameters, could be correlated with pilot opinion.

We are now convinced that task performance in the usual sense cannot necessarily be correlated with pilot opinion. This might be summed up by saying that although a pilot can perform a tracking task accurately and smoothly with a high-friction system, he does not necessarily like it. In an effort to obtain better correlation with pilot opinion, while still maintaining task-performance evaluation, the parameter $\int_0^{60} (|F_s|dt/60)$ was added. The product of

$$\int_0^{60} \frac{|\Delta n_z|dt}{60} \quad \int_0^{60} \frac{|E_n|dt}{60} \quad \int_0^{60} \frac{|F_s|dt}{60}$$

(*g*-ft-lb) vs Cooper Rating for the Task A runs is shown in Fig. 12.

We considered that Figure 12 shows reasonable correlation between the *g*-ft-lb parameter and pilot opinion for the Task A problem. The *g*-ft-lb parameter can be thought of as a "task performance" parameter in a sense that is broader than usual. Performance now includes both accomplishment and the ease with which it is accomplished.

Figure 13 shows a plot of *g*-ft-lb vs friction for three force gradients and zero preload using the Task A problem. Each point plotted represents an average of the reports from all the pilots who flew under this particular condition. Note the predominant effect of friction when compared to changes in the force gradient. Comparison of Fig. 13 with Fig. 12 indicates a change from a Cooper Rating of 3.5 at a friction level of 1 lb to a Cooper Rating of 7.0 at a friction level of 5 lb.

Figure 14 is a direct plot of Cooper Rating vs friction for three different pilots at zero preload and a stick sensitivity value of 0.177 in./*g*.

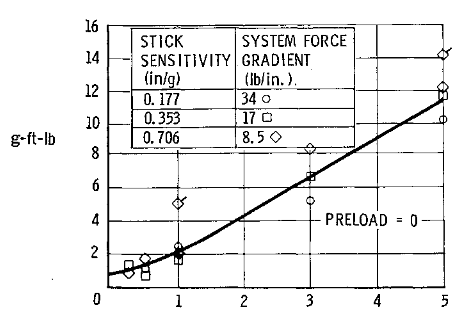

Fig. 13 Friction effect on *g*-ft-lb parameter (Task A).

The average change in Cooper Rating (ΔCR) for the change in friction from 1–5 lb was 2.5 units, or one unit less than that obtained by using Figs. 12 and 13.

The absolute values varied more widely and reflect pilot bias. Pilot *A*, our favorite, correlated very closely with both the (ΔCR) and absolute values obtained from introducing the *g*-ft-lb values from Fig. 13 into Fig. 12. In any case, a change from 1 to 5 lb of friction created a degradation in Cooper Rating of 2.5 units, even though stick force per *g*, natural frequency and damping, stick sensitivity in in./*g*, and surface response were all maintained at near optimum values.[4] Reduction of friction values below 1 lb resulted in further reduction of the *g*-ft-lb parameter and improvement in the Cooper Rating.

Figure 15 is a plot of *g*-ft-lb vs preload for Task A with friction held constant at 1 lb. Although more data is needed in the higher preload area, the increase in preload increased the *g*-ft-lb value at a much slower rate than equivalent increases in friction. Comparison with pilot opinion reflected the same trend, and it was generally concluded that additional preload slightly deteriorated the ability to fly the Task A maneuver.

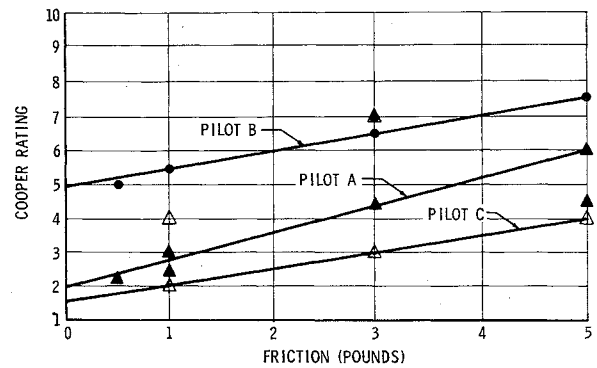

Fig. 14 Friction effect on Cooper rating (Task A).

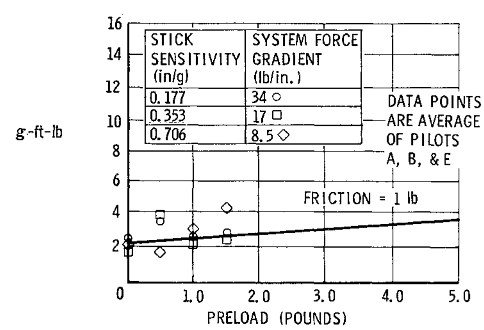

Fig. 15 Preload effect on the *g*-ft-lb parameter (Task A).

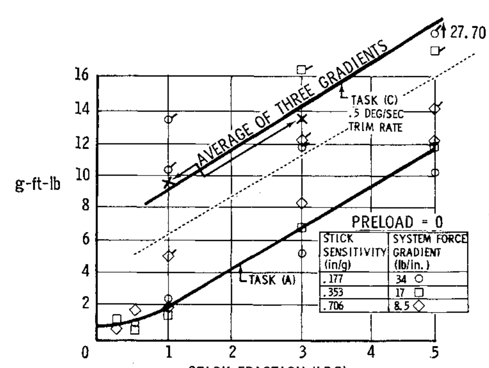

Fig. 16 Friction effects on the *g*-ft-lb parameter (Tasks A and C).

The task B maneuver was chiefly distinguished by its insensitivity to variation in friction, preload, and gearing. Variations in Cooper Rating and scoring values were small and undisciplined.

Figure 16 is a plot of g-ft-lb vs friction for Task C superimposed on the same plot originally shown for Task A as Fig. 13. The scatter for changes in stick sensitivity is greater, but the slope of g-ft-lb increase with friction increase is similar. Cooper Rating correlation with g-ft-lb was not quite so good for Task C as for Task A but was still reasonable.

Figure 17 is a plot of trim rate vs g-ft-lb, which indicates an optimum trim rate of approximately 1.5°/sec.

Variations in stick damping from 1 lb/in./sec to 75 lb/in./sec made little difference in either Cooper Rating or g-ft-lb values in performing the Task C maneuver.

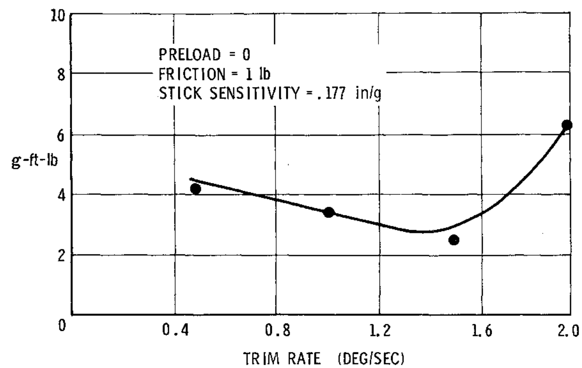

Fig. 17 Trim rate effect on the g-ft-lb parameter (Task C).

Remarks

The g-ft-lb parameter as developed and used in this paper concerns the controversial area of performance measurement.[5] It is generally agreed that the assessment of a man-machine system, in this case a pilot-airplane combination, should combine two features: task performance as measured by some average error, and insight into the ease with which the task is accomplished.[6] What is not so generally agreed upon is how the assessment can best be made. Pilot opinion, as disciplined by Cooper Rating, is probably the present most popular method of what might be called total performance measurement. In our case, reluctance to rely completely on the Cooper Rating technique, and possibly some of the naïvete mentioned earlier, led to the development of the g-ft-lb parameter. This parameter (g-ft-lb) has limited generality. The performance error measurements $\int_0^{60}(|E_h|dt/60)$ and $\int_0^{60}(|\Delta n_z|dt/60)$ are oriented to the specific tasks selected, and the average stick force term $\int_0^{60}(|F_s|dt/60)$ would not always serve as a primary index of the ease with which a selected task is accomplished.

Conclusions

These conclusions are considered warranted with respect to the small stick deflection area.

1) Friction is the most significant control-system property in the small stick deflection range of flying. Reduction of friction below values of 1 lb continued to improve handling qualities in this fixed-base simulation.

2) Task performance in the usual sense cannot necessarily be correlated with pilot opinion.

3) The g-ft-lb parameter shows promise for future use in testing of this type, as an adjunct to Cooper Rating.

4) Gearing and stick sensitivity in terms of stick displacement per g was not a significant variable in all testing accomplished.

5) For a given amount of friction, addition of preload did not improve the flying qualities in all testing accomplished.

6) The trim rate at this flight condition was indicated as optimum at about 1.5 stabilizer degrees per sec. This corresponded to 3 g's per sec for the airplane under consideration.

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