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FORCE MODIFICATION AND DEFLECTION LOSS COMPENSATION TO THE PILOT'S CONTROLS IN AN AIRCRAFT SIMULATOR

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16. Abstract

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The study of the deflection losses indicates that the major cause is a structural or mechanical distortion that is linear with applied force. Thus, the phenomena may be modeled and, subsequently, compensation for the losses may be made in the associated simulation computer.

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SYMBOLS

F	force applied by pilot on a control such as the wheel
G_B	basic force gradient obtained within the control force loader electromechanical system
G_T	total or true force gradient of a control
K	bend coefficient
L	length of column or stick
S_1,S_2,S_3	100-V scale factors on δ_c, ΔF, and F, respectively
v_1,v_2,v_3	voltages representing scaled δ_c, ΔF, and F
δ	actual control deflection
δ_c	computed control deflection
ΔF	modifying force resulting from force gradient modification

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SUMMARY

Control loader systems are used widely in flight simulator cockpits so that pilots may experience the correct forces while manipulating the flight controls. Two simulators at Ames Research Center - the Flight Simulator for Advanced Aircraft (FSAA) and the Moving Cab Transport Simulator (MCTS) - contain control loader systems that exhibit small control deflection losses at high forces. These losses make force calibration and documentation difficult and also may cause losses in control authority of the simulated aircraft.

The study of the deflection losses indicates that the major cause is a structural or mechanical distortion that is linear with applied force. Thus, the phenomena may be modeled and, subsequently, compensation for the losses may be made in the associated simulation computer.

INTRODUCTION

Control force loaders are the systems in an aircraft simulation that provide the pilot with the flight control force characteristics from the true aircraft. It is highly desirable that the force the pilot feels from the controls in the simulator be a faithful representation of the force in the aircraft. Most large aircraft flight simulators contain loader systems, in particular, the Flight Simulator for Advanced Aircraft (FSAA) and the Moving Cab Transport Simulator (MCTS) at Ames.

In addition to inertia and damping modeling, the system is mechanized to obtain a force versus control deflection profile. Because of the nature of the loader system, force modeling is difficult and results can be somewhat inaccurate, possibly to the extent that errors are introduced in the controllability of the simulated aircraft. Obtaining the specified force gradient required a disproportionate amount of the total simulation modeling time, primarily because of unknown mechanical deflection losses inherent in the system and an incomplete understanding of the operation of the loaders. As a result of studying the system, an effective and efficient method of calibrating the control forces and deflections is presented. In addition, the method by which forces may be modified under in-flight simulation conditions and the method of compensation of the major control deflection losses are presented.

CONTROL FORCES IN THE FSAA AND MCTS

Where close fidelity between simulator and aircraft is required, much attention is given to the simulator environment of the pilot. For example, visual scene simulators portray the landscape, the motion of the cockpit produces the desired accelerations on the pilot, and adequate instrumentation provides the same flight information as that in the actual aircraft. The same fidelity is desired of the pilot controls; the pilot's hands should exert the same force, for example, that they would in the actual aircraft while performing a particular maneuver.

The control force system in the simulator cabs of the FSAA and the MCTS presently provides a control centering force, a force gradient, inertia, friction (hysteresis), bob weight, and damping adjustments. The control characteristics from an actual aircraft are tailored on the control force loading system of the simulator. Since nearly all these adjustments are made with hand-turned potentiometers, there is little modification of the characteristics possible while the simulator is under flight conditions during a test run. One notable exception is the force gradient, G_T, the proportionality constant between the pilot's force on a control and its deflection due to that force.

In many simulations, the pilot control force is not only a function of the control deflection, but also of dynamic pressure or some other related physical phenomena; in any case, it is a varying quantity. Consequently, the force gradient itself must vary. This requirement prompted modifications to the electronics section of the control loading system to supplement the potentiometer adjustment of force gradient, thereby making a variable gradient possible. Once this feature was available, it became apparent that some serious difficulties in calibrating the loading system for variable force-deflection relationships existed. The problem manifested itself in the following way: When a range of gradients are needed in the simulation, normally the lowest value is set into the loading system itself and all higher gradients are added to this "basic" low gradient through the abovementioned modification. The voltages from the loader system electronics which represent force and control deflection would be calibrated (scaled) in this low gradient case. However, when the high gradients were checked, low voltages indicated a loss in control deflection. Since the actual maximum control deflection remained constant for high and low gradients, the loss was considered to be within the electromechanical system. The problem was to isolate or compensate for control deflection losses in the variable force gradient cases. A study indicated that three operational and physical aspects contribute to the loss: (1) bend in the mechanical linkage or structural members of the system, (2) observation errors in the data gathering process of calibration, and (3) errors that result from the use of control deflections (such as the column or elevator control) in linear measure rather than angular measure.

Loader System and Gradient Modification Model

A simple model of the system is shown in figure 1 for the column control or pilot stick. The system operates as follows: When the pilot applies a force to the stick, which produces the actual stick deflection, the strain gauge generates a voltage proportional to the force F that is input to an analog computer representation of a mass-spring-damper system. The output, the computed deflection δ_C, is used to drive a servomechanism (represented by the solenoid circuit in the figure) and the position feedback circuit ensures proper positioning. This procedure generates an opposing force back through the mechanical linkage to the pilot.

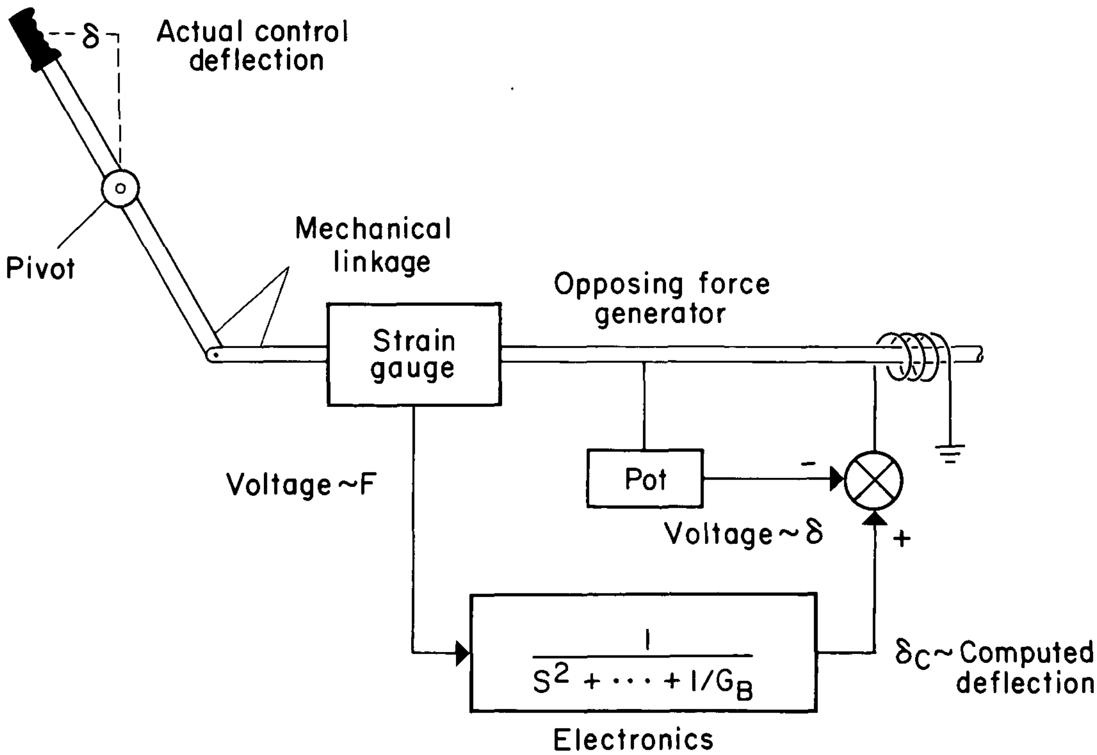


Figure 1.- Simple model of control force electromechanical system on a simulator pilot stick.

In figure 1, the force gradient attainable within the loader electronics is represented by G_B, the basic gradient. If the simulation requires that the gradient be changed as a function of a variable within the aircraft simulation (dynamic pressure, for instance), the variability must be external to the gradient potentiometer. Figure 2 shows the procedure used to vary the gradient. The desired total gradient G_T is generated within the aircraft simulation computer, the basic gradient is subtracted from G_T, and the difference is multiplied by the computed deflection. The net effect of combining the potentiometer-set G_B and subtracting G_B in the multiplier feedback loop is the desired force gradient G_T.

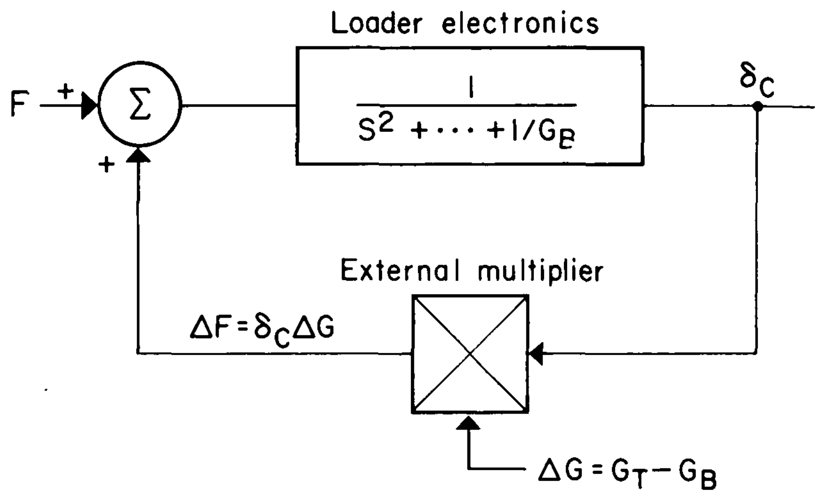


Figure 2.- Force gradient modification control diagram.

SOLUTIONS TO OPERATIONAL PROBLEMS IN GRADIENT MODIFICATION

Each attempt to install specified force-deflection characteristics on the loader system is clouded by operational and system problems. The problems result from control deflection losses, calibration procedures, and nonlinear measurements. Each affects the setup and calibration of the loader to varying degrees.

Control Bend Problem

A serious anomaly occurred when plots of actual control deflection, δ, versus the computed deflection, δ_c, were compared at different force gradients. The effect of increasing gradient is to decrease δ_c for a given δ. Thus, if the voltage proportional to δ_c is calculated at an actual control deflection, say at maximum control throw, at a low gradient, and if δ_c is checked when at a higher gradient, the computed value will have diminished thus indicating a loss in the control deflection. This phenomenon not only has adverse effects on the determination of a particular gradient, but it lessens the control power of the control surface on the simulated aircraft, perhaps making it uncontrollable under adverse conditions.

From an inspection of data from the loader system, it appeared that most of the deflection loss was purely mechanical, due to either bending of members in the mechanical linkage of the system or flexing of the structure upon which the loader system is mounted. The flextures are small, but small position losses from structural bending become large at the pilot's end of the system because of the mechanical advantage in between.

Rather than trying to strengthen the mechanical hardware, the approach used to alleviate the problem was to first model the system losses and then to compensate for them computationally totally within the external simulation computer. It was felt that, so long as the aircraft simulation used the correct control input for a given pilot force, the particular method of cure was immaterial.

The following model was adopted. Let

$$\delta_c = \delta - KF \tag{1}$$

where F is the force applied to the control and K is the inverse of a spring constant and a positive number. Thus, for a given value of actual control deflection δ, as the force F increases, the computed control deflection decreases. The loss in deflection is KF.

The value of K is difficult to determine when the actual voltages that represent the variables δ_c and F are used. Figure 3 shows the system for

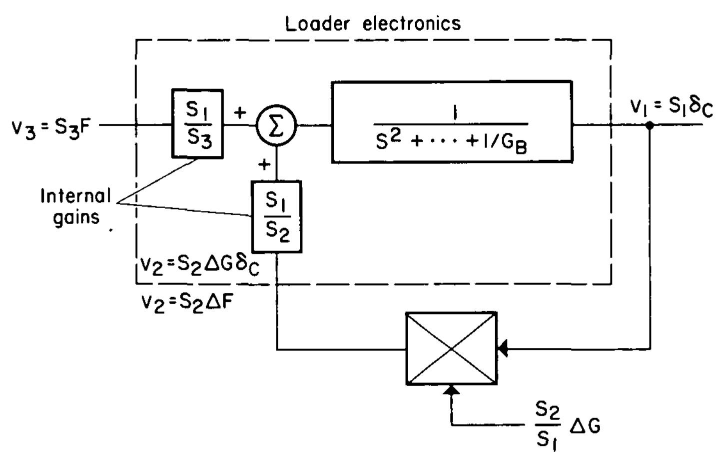


Figure 3.- Voltage or scaled variable representation of control loader system.

the voltage calibration or scaling associated with each important variable. The S_i terms are the voltage scale factors; the voltage v_1 is proportional to δ_c by

$$v_1 = S_1\delta_c \tag{2}$$

If equations (1) and (2) are combined, one obtains

$$v_1 = S_1\delta - S_1KF \tag{3}$$

It is apparent that we have one equation with two unknowns, S_1 and K. However, by taking two accurate sets of data (v_1, δ, F) from the loader experimentally, one can solve for S_1, the scale factor, and, K, the bend coefficient. However, more than two sets of data should be taken, in fact, the more the better, to reduce the chance of observational data-taking errors. From these data, the method of least squares can be used to provide a polynomial fit to the data in the form

$$v_1 = a\delta + bF \tag{4}$$

(see appendix A for details). Equating coefficients from equations (3) and (4) yields

$$S_1 = a \tag{5a}$$

$$K = -b/S_1 \tag{5b}$$

Once the voltage scale factor and the coefficient are determined, the actual control deflection δ may be calculated in the digital simulation computer from the input variables δ_c and F. Thus, compensation for the control losses due to bend is accomplished.

As an example of the idea, data were obtained from the column control loader arrangement used in simulations of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA) on the FSAA. The significance of this is that a particular length of column utilizing particular mechanical advantages and electronic gains was used. These may all vary from simulation to simulation, so that bend coefficients and scale voltage factors will normally vary. Figure 4 shows data taken at several gradients and the polynomial fit obtained by the least squares method. Note the bend coefficient is 0.928 m/N (0.016 in./lb).

To evaluate the effect of this loss since

$$F = G_T\delta \tag{6}$$

where G_T is the force gradient specified, one may write, from equation (1),

$$\delta_c = \delta(1 - KG_T) \tag{7}$$

Now if δ_c were calibrated at a low gradient and the calibration used at a higher gradient, the loss in δ_c could be found (for a constant δ) by differentiating equation (7) to obtain

$$\Delta\delta_c = -\delta KG_T \tag{7a}$$

In the simulation of the AWJSRA, the worst case occurred at $\delta = 0.0508$ m (2.0 in.) and G = 2155.2 N/m (12.5 lb/in.). At $\Delta\delta_c = -0.010$ m (-0.4 in.), a 20 percent loss in computed column occurs at an actual column displacement of 0.0508 m (2.0 in.). At the full column deflection of 0.788 m (7 in.), $\Delta\delta_c = -0.914\times10^{-2}$ m (0.36 in.) or only about 5 percent of its actual travel was lost.

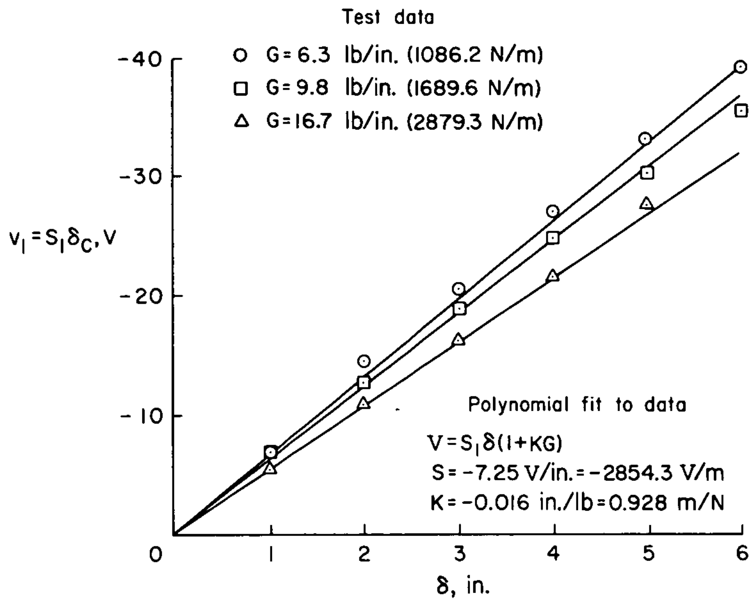


Figure 4.- Comparison of test data and the polynomial fit for the augmentor wing jet STOL research aircraft column control in the FSAA cockpit.

A word of caution is due when one collects data to determine K. Since a wide latitude in mechanical advantage and electronic gains exists within the loader system, one should be sure that these parameters are fixed before any data are taken. Normally, these gains are set and left fixed when the maximum force is known in advance. Naturally, if any changes occur in these gains, the entire procedure must be reinitiated. Another suggestion is to collect data at several force gradients within the expected range of the simulation specification. This precaution should give a more representative result than if only one gradient value were used. Normally, data collection from four or five gradients at four or five deflections should be sufficient.

Gradient Modification With Bend Compensation

Providing for the capability of variable gradients is complicated somewhat by the compensation for bend losses. Since a basic gradient is set within the electronic section of the loader system, it is effectively multiplied by δ_c, the computed deflection, which is in error. Thus, it is apparent that not only the gradient must be varied, but the deflection variable must be compensated as follows: from equation (6),

$$F = G_T \delta$$

the desired relationship between pilot force, total true gradient, and actual control deflection. However, the loader computer calculates

$$F_L = G_B \delta_c \tag{8}$$

where F_L is the actual force available from a basic gradient and the computed deflection. If

$$F_{mod} = F - F_L \tag{9}$$

is the modifying force needed, then, from equations (6), (8), and (9),

$$F_{mod} = G_T \delta - G_B \delta_c \tag{10}$$

If equation (7) is substituted into (10),

$$F_{mod} = \left(\frac{G_T}{1 - KG_T} - G_B \right) \delta_c \tag{11}$$

and the variable ΔG of figures 2 and 3 in its compensated form is

$$\Delta G = \frac{G_T}{1 - KG_T} - G_B \tag{12}$$

as shown in figure 5. Figure 5 also indicates how the scaled variable δ_c must be modified to plot the true deflection for documentation. Normally, complete X-Y plots of force versus deflection are provided to document the static force characteristics for each of the three primary controls: column, wheel, and pedals.

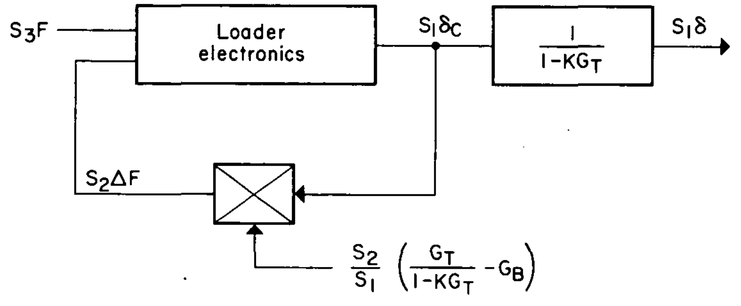


Figure 5.- Schematic diagram of the control loader incorporating compensation for control bending.

The modifying gradient, ΔG, is normally calculated in the digital computer while ΔG is multiplied by δ_c on an analog computer multiplier. This "hybrid" technique was found necessary after the multiplication and processing on the digital computer produced unsatisfactory discrete step forces at the control. Pilots simply would not tolerate the discrete jumps, particularly in the column and wheel.

An example of the logic needed for a two-segment force gradient curve is given in the flow chart in appendix C. It includes the necessary bending compensation.

Voltage Calibration and Observation Errors

In the early operational phases of calibration of the system, the scale factors S_1 (for computed deflection); S_2 (for the modifying force); and S_3 (for the pilot input force) must be determined. The scale S_1 is determined along with the bend coefficient as described earlier.

An operational problem occurs when data needed for the scales are collected. The data consists of voltage readings and direct measurements from spring scales and ruler or protractor scales. Data collection is difficult to do physically because the force must be held constant manually, while the position and force calibration instruments are read and while the voltages are recorded. This difficulty has been the source of many errors in calibrations. Experience dictates that many readings should be taken to ensure that observation errors are averaged out.

Once several sets of data are taken, calculating the force scale factor S_3 is a straightforward averaging process; for example,

$$S_3 = \frac{1}{n}\sum_{i=1}^{n}\frac{V_{3_i}}{F_i} \tag{13}$$

The calibration of the added force term is somewhat indirect. If the values of the internal gains S_1/S_2 and S_3/S_2 are known (fig. 3), simple ratios can specify S_2. An experimental method can be used instead of these numbers:

1. The control is moved to a fixed position with $v_2 = 0$; v_1 and v_3 are then noted.

2. Replace the multiplier with a voltage supply, then vary the voltage v_2 until v_1 is the value noted above. At this step, the control must be at the null position so that $v_3 = 0$. The scale S_2 is then

$$S_2 = v_2 S_3 / v_3 \tag{14}$$

(See appendix B for a derivation.) Again, several data sets should be taken to average out observation errors.

Mechanical Nonlinearities

A minor difficulty arises in calibrating the column travel since its deflection is measured in a horizontal plane, while the column handles move in an arc. If it is assumed that the mechanical linkage moves proportional to the angular displacement, the deflection is in error at large angles. The deflections are:

$$\delta = L \sin \theta \tag{15}$$

in the horizontal plane and

$$\delta = L\theta \tag{16}$$

if measured along the arc, where θ is the angle and L is the stick length. Since

$$\sin \theta \cong \theta - (\theta^3/6) \tag{17}$$

the relative error of the horizontal and arc measure is approximately $\theta^2/6$ or θ must exceed 14° to be in error by 1 percent or 20° for 2-percent error. Wheel deflections do not suffer from this, but rudder pedal deflections are traditionally measured in inches also, thus errors are induced. Normally, errors of this magnitude are ignored.

CONCLUSIONS

The problems encountered in calibrating the control loaders in the FSAA and the MCTS are of two types: voltage calibration uncertainty and control power loss. The first problem is relatively simple and requires the use of enough data to average out observation errors. The loss in control power, however, is a more serious and difficult problem. As the simulation of the augmentor wing jet STOL research aircraft illustrates, 5 to 20 percent of the column control power would be lost if no compensation were used. For simulations of aircraft using the MCTS or FSAA simulators that require control force gradient modification, it would be wise to use the compensation procedures described here.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Feb. 4, 1974

APPENDIX A

DERIVATION OF LEAST-SQUARES METHOD CURVE FIT OF A TWO-VARIABLE, FIRST-ORDER POLYNOMIAL

For n sets of data on v, δ, and F, assume that $v = a\delta + bF$ and a and b are unknown. Let $u = a\delta + bF - v$ and

$$f = \sum u_i^2 = (a\delta_1 + bF_1 - v_1)^2 + . . . + (a\delta_n + bF_n - v_n)^2.$$

Differention yields

$$\frac{\partial f}{\partial a} = 2\sum \delta_i(a\delta_i + bF_i - v_i)$$

and

$$\frac{\partial f}{\partial b} = 2\sum F_i(a\delta_i + bF_i - v_i)$$

Setting the partials to zero ensures a minimum in the square error function f. Thus,

$$a\sum \delta_i^2 + b\sum \delta_i F_i = \sum \delta_i v_i$$

$$a\sum \delta_i F_i + b\sum F_i^2 = \sum F_i v_i$$

Solving for a and b by Cramer's rule yields

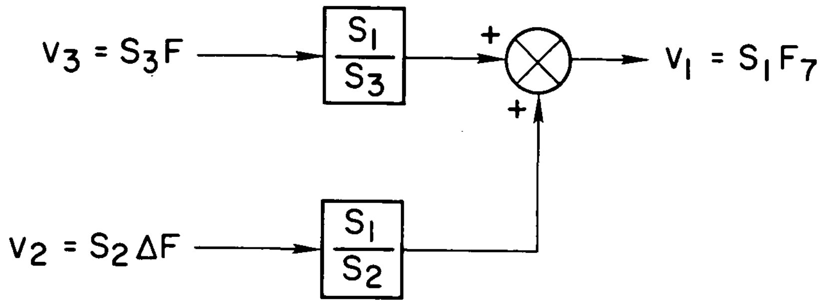
$$a = \left(\sum F_i^2 \sum \delta_i v_i - \sum F_i v_i \sum \delta_i F_i\right) \Big/ \left[\sum \delta_i^2 \sum F_i^2 - \left(\sum \delta_i F_i\right)^2\right]$$

$$b = \left(\sum \delta_i^2 \sum F_i v_i - \sum \delta_i v_i \sum \delta_i F_i\right) \Big/ \left[\sum \delta_i^2 \sum F_i^2 - \left(\sum \delta_i F_i\right)^2\right]$$

APPENDIX B

DETERMINATION OF THE MODIFYING FORCES SCALE FACTORS

From figure 3,



then

$$v_1 = S_1F_T = S_1v_3/S_3 + S_1v_2/S_2$$

In a two-step process, let v_2 and v_3 be zero with v_1 held constant. With $v_2 = 0$, that is, with only a specific constant force F being exerted,

$$v_1 = S_1v_3/S_3 = \text{const}$$

When $v_3 = 0$, apply the voltage v_2 until

$$v_1 = S_1v_2/S_2 = \text{const}$$

Then equating for these cases where v_1 = const yields

$$S_1v_3/S_3 = S_1v_2/S_2$$

Thus,

$$S_2 = v_2S_3/v_3 = v_2/F$$

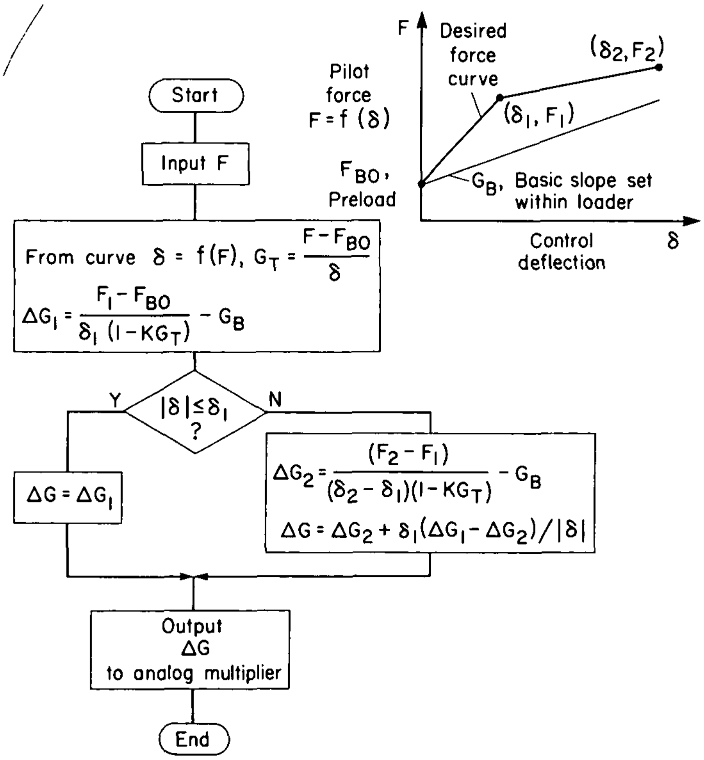
APPENDIX C

PROGRAM FLOW CHART FOR A TWO-SEGMENT FORCE CURVE INCLUDING BEND COMPENSATION

The force exerted by the pilot is

$$F = F_{BO} + G_B\delta_c + \left(\frac{G_T}{1 - KG_T} - G_B\right)\delta_c$$

where the first two terms are electronically generated within the loader system. Terms previously undefined in the flow chart are self-evident in the force plot.



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