ADA950315

(14) DOUGLAS PAPER-5114

(6) EVALUATION OF A FLY-BY-WIRE SYSTEM

(11) 1968

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(12) 37

presented to
SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
SAE COMMITTEE A-6
AEROSPACE FLUID POWER AND CONTROL TECHNOLOGIES
OF THE
SAE AEROSPACE EQUIPMENT DIVISION
Sheraton-Dayton Hotel
Dayton, Ohio
May 3, 1968

Released

DOUGLAS AIRCRAFT COMPANY

MCDONNELL DOUGLAS
CORPORATION

116400

C-112293 Copy No. 1

EVALUATION OF A FLY-BY-WIRE SYSTEM

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ABSTRACT

The design of a Fly-By-Wire system is described which is based on applications of active redundancy and electrical feedback techniques. The replacement of mechanical flight control systems with Fly-By-Wire systems for flight control of large high-speed aircraft is advocated because of performance deficiencies in mechanical systems. The Fly-By-Wire system incorporates three redundant channels over which three electrical flight command signals are continuously transmitted to the aircraft control surface power actuator. A breadboard model of one axis of the Fly-By-Wire system was fabricated and evaluated for performance under various failure conditions. Results of the tests demonstrate the feasibility of design techniques with which the three electrical signals are converted to mechanical signals and combined to provide a single input to a hydraulic power mechanism.

INTRODUCTION

The ability of a pilot to control the flight path of a high performance aircraft depends largely on the precision with which his flight commands are transmitted to the control surface actuators. Traditionally, the pilot's effort was applied directly to the elevator, aileron, and rudder over a system of cables, cranks, and pulleys. However, the power required for surface control in high speed, military aircraft far exceeds the pilot's capabilities. Flight control systems installed in these aircraft are fully powered -- that is, none of the force required to overcome, the aerodynamic moment on the control surface comes from the pilot's control stick or pedals. The surfaces are driven by hydraulic actuators, and all control power is supplied from hydraulic pumps driven by the aircraft engines.

Typically, the hydraulic power to the surface actuator is controlled by a slide valve, the rate of flow of the hydraulic fluid to the actuator being proportional to the displacement of the valve slide. The valve is driven by a mechanical device according to the difference between the position of the control surface and the position commanded by the pilot's control stick or pedals. Thus, the power mechanism which drives the surface is a closed loop servomechanism, controlled by a single, low-power, command signal represented by the mechanical position of the input member of the power mechanism.

Development of fully powered flight control systems has prompted a search for a means of transmitting the pilot's flight command to the power mechanism which does not have the performance limitations imposed by conventional mechanical methods. These performance limitations are the result of the remoteness of the control surface from the pilot, and restrictions on the routing of the mechanical linkages. Long cable runs and numerous changes in direction of cables have resulted in excessive compliance and friction. In larger aircraft, structural deflection, thermal differential expansion, and the inertia of mechanical parts have resulted in serious design problems. The obvious alternative to a mechanical command system is the transmission of the flight command signals in the form of electrical currents or voltages. Flight control systems in which the command signal is transmitted electrically are known as "Fly-By-Wire" systems, see Reference 1.

Electrical flight command transmission systems have, in fact, been in use for many years in the form of automatic flight control systems. Automatic systems, however, have not replaced the mechanical system; but are in addition to, and intended to augment, the conventional system. Even in those aircraft having complete control stick steering systems, in which the pilots flight command is transmitted through the automatic system, the conventional cable system must be retained as a backup because of its inherently higher reliability.

Various techniques have been suggested for increasing the reliability of electrical methods of transmitting the flight command from the pilot's stick to the input of the power mechanism. These techniques are: simplification of the system over which the flight command signal is transmitted, design of the signal transmission system to permit use of more reliable components, and incorporation of extra components or subsystems to perform the signal transmitting functions when original components have malfunctioned. Numerous systems have been proposed which incorporate some or all of these techniques. Some of these systems have been built and installed in aircraft. To this date, however, no aircraft is known to have Fly-By-Wire in all three axes of the control system, nor has the mechanical control system been eliminated from more than one flight control axis. Presented herein is an evaluation of improvement in reliability and performance over that of currently proposed electrical flight control systems.

SYSTEM DESIGN

OBJECTIVES

The objectives of the evaluation program described herein are:

1. To select a design approach to a Fly-By-Wire control system which is compatible with the flight control requirements for aircraft of advanced design, and which offers a potential for significant improvement over currently proposed electrical flight control systems.

2. To design and fabricate a breadboard model of a single-axis Fly-By-Wire system, based on the selected design approach and on use of present state-of-the-art hardware.

3. To perform a laboratory testing program which evaluates the feasibility of the design approach and determines the performance capability of the model flight control system.

DESIGN REQUIREMENTS

Prior to selection of the design approach to be evaluated, the following requirements and restrictions for the design of the system were established.

1. The control surface actuator shall be controlled by electrical signals proportional to the position of the pilot's control stick. The method selected for conversion of the mechanical displacement of the control stick to electrical signals shall offer a high level or performance and reliability.

2. The design shall incorporate a provision for summation (at a common junction) of flight command signals from a pilot's control stick and an automatic flight control system.

3. Redundancy techniques shall be applied to the design of all parts of the system which transmit the electrical flight command signals.

DESIGN APPROACH

Redundancy

Selection of the design approach for the Fly-By-Wire system was primarily a choice of redundancy techniques. There are two general techniques for incorporating redundancy into a control system.

These techniques are usually known as standy redundancy and active redundancy.

In a system employing the standy technique, only one set of redundant parts controls the output of the system; the remaining parts of the system are standing by, unused. Upon a failure in the controlling set of parts, the failed parts are switched out of the system and the standby parts are switched in.

In systems which employ the active redundancy technique, all redundant parts are active and continuously controlling the output of the system. Upon failure of one set of redundant parts, the remaining parts counteract the effect of the failure.

Each of these redundancy techniques presents serious design problems. The monitoring and switchover devices necessary to the operation of the standby redundancy are subject to failure and may require additional redundancy for sufficient reliability. The switchover device must operate nearly instantaneously in order to prevent excessive transients at time of failure.

The most difficult problem in the design of the active redundant system is the method by which the output signals of the redundant parts are recombined to control a single power output. This formation of a composite signal can be accomplished by force summing or displacement summing of the mechanical signals. The output of the summing device is, in either case, the average of the signals. The abnormal signal in the failed parts of the system must be counteracted by an equal and opposite signal in the unfailed system, see Reference 2.

To meet the fail-operative requirement, a Fly-By-Wire system must have at least three redundant signal channels. The monitor of the standby redundancy system cannot detect which of two signals is abnormal. In the active redundancy system, one channel is expended in counteracting an abnormal signal in a failed channel, and a third channel, with normal signal, is needed for control of the system.

The redundancy technique selected for the design of the system to be evaluated is the active type. This technique was chosen because of the availability of a new device that performs the function of recombining the three signals at the output of the three redundant channels to form a single output. This new technique solves the most serious of the design problems inherent to the active redundancy system. The device which performs this signal-selecting function is called a voter mechanism. Its operation is described later in this paper.

Feedback Control

The closed-loop, feedback control system technique was selected as a basis for design of the system. The output of the system is differentially summed with the input to the system in a summing amplifier. The difference between input and output is the system error, which is amplified to drive the system. All feedback signals are converted to electrical form prior to summing. The Fly-By-Wire system incorporates three complete closed-loop, feedback control subsystems.

SYSTEM DESCRIPTION

The Fly-By-Wire flight control system is a triply redundant electrical system which controls the position of a hydraulic power mechanism according to flight control commands originating at a pilot's control stick. The system evaluated under the program reported herein is depicted in simplified form in the schematic diagram of Figure 1. Components of the system are combined and arranged, employing feedback control system techniques, to position an aircraft control surface (elevator, aileron, or rudder) for the control of the flight path of the aircraft according to electrical flight commands transmitted from the pilot's cockpit to the power mechanism.

The principle parts of the system are: a hydraulic power servo actuator assembly, capable of accepting three electrical signal inputs; three channels of electronic demodulators and amplifiers; and four sets of electrical position transducers.

Servo Actuator Assembly

The primary component of the Fly-By-Wire system is the servo actuator assembly. The servo actuator package is shown on Figure 2. It is an assembly of electromechanical, electrohydraulic, and hydromechanical devices, designed and arranged so as to produce a single high-power-level output which properly follows three independent, but similar, low-level signal inputs. The following paragraphs list these devices, together with a brief statement of their functions.

Three electrohydraulic servo valves are mounted on top of the servo actuator housing. These devices are single-stage valves, each consisting of a dc electric torque motor and a jet pipe hydraulic amplifier. The torque motors accept the three electrical signal inputs to the servo actuator. The jet pipe hydraulic amplifiers drive three modulating pistons.

A modulating piston is installed directly under each transfer valve within the actuator housing. The displacement of each of the three modulating pistons is an independent signal input to the voter mechansim.

The voter mechanism consists of a shaft, three lever arms, and an output crank. Each lever arm is driven by a modulating piston, and is coupled to the shaft through a roller-detent mechanism which has a saturating torque characteristic. The output of the voter mechanism is the position of the output crank. The crank directly drives the slide of the actuator slide valve.

The power slide valve meters hydraulic fluid flow to the power cylinder according to the position of the slide as determined by the voter mechanism position. The slide valve configuration is dual tandem -- that is, it has a single slide with two sets of lands and grooves. The slide valve controls power to the tandem power cylinder from two hydraulic supplies.

The power cylinder is the output device of the servo actuator assembly. It drives the control surface to a position determined by the flow from the slide valve. The device consists of two hydraulic pistons in tandem. The piston rod position is the output of the servo actuator.

The servo actuator assembly is equipped with three sets of position transducers. One set of transducers is installed in the piston rod of the power cylinder and transmits the output position of the actuator. A second set is installed on the slide of the dual tandem slide valve; the valve transducer signal represents the position of the valve slide and also the position of the output of the voter mechanism. A third set of transducers is installed to transmit the positions of the three modulating pistons. The actuator position transducers are tandem -- that is, they are physically in line, coaxial, and their armatures are driven by a single rod. The slide valve position transducer set is also a tandem assembly. The transducers installed on each of the three modulating pistons are, however, mechanically independent. Each transducer, in a set of three, is entirely electrically independent of the other two transducers in the same transducer set.

Three solenoid valves are installed on top of the servo actuator housing -- one solenoid valve adjacent to each electrohydraulic servo valve. The purpose of the solenoid valves is to provide means of electrically shutting off the hydraulic pressure to the jet pipe hydraulic amplifier in each of the three electrohydraulic servo valves. The valves are normally closed -- that is, they open when electrically energized and close when de-energized. The solenoid valves operate from 28-volt dc electric power.

Control Stick Transducer Assembly

A tandem assembly of three position transducers is mechanically coupled to the pilot's control stick. Each section of the control stick transducer assembly transmits an electrical voltage proportional to the control stick position. The control stick transducer assembly is shown in Figure 3. It is electrically identical to the actuator output position transducer in the servo actuator package.

System Electronics

Electronic demodulators, voltage amplifiers, current amplifiers, summing circuits, and gain-changing devices are incorporated into three identical channels in the Fly-By-Wire system. Each channel forms a flight command signal path from each of the three control stick transducers to the control winding of the torque motor in the corresponding electrohydraulic servo valve at the servo actuator. The three channels are packaged in separate units and operate independently of each other.

SYSTEM OPERATION

The basic function of the Fly-By-Wire system developed under this program is to electrically control the output position of a power mechanism driving an aerodynamic control surface. The system operation is based on the closed-loop techniques of feedback control systems, in which the basic driving function is the difference between input command and output position. The driving signal is the difference between the actual position of the output servo actuator and the commanded position of the actuator. Electric signals proportional to the output position and to the commanded output position are generated by position transducers installed at the control surface actuator and the pilot's control stick, respectively.

The output position signal and the command signal are of opposite electrical polarity. Algebraic summation of the two signals produces a difference voltage which is referred to as the error signal. A closed loop is formed at the summing junction, around which the error signal makes a complete circuit of the system. This closed loop will be called the actuator loop or the outside loop. A functional block diagram of the Fly-By-Wire system is shown in Figure 4. As shown on the diagram, the majority of the components making up the signal-handling portions of the system have been installed in triplicate. The system has, in fact, three complete and separate channels of the signal-handling equipment between the control stick and the power mechanism. In effect, the system is triply redundant as concerns electrical signals.

It can be seen from the block diagram that each channel is, by itself, a closed-loop position servomechanism. The closed loop consists of the channel electronics (demodulators and amplifiers), an electrohydraulic servo valve, and a modulating piston. The position of the modulating piston, which represents the output of this closed loop, is converted to an electrical signal by a position transducer. Demodulation and summing of the modulating piston position signal at the channel summing junction completes the loop closure. This closed loop in each channel will be called the modulating piston or inside loop.

Operation of the inside loop can be best understood by considering the modulating piston as the output servo actuator of a piston servomechanism -- the output position being fed back from the modulating piston transducers to the summing junction. The resulting error voltage is amplified and converted to a current which flows through the control windings of the electrohydraulic servo valve torque motor, which drives the jet pipe in the hydraulic amplifier. Displacement of the jet pipe in the valve generates a differential hydraulic pressure which displaces the modulating piston. The position of the modulating piston is the output signal of each channel.

The three similar flight command signals are thus transmitted over three independent channels and are represented at the output of each channel by the position of a modulating piston. It can be seen that, except for restrictions imposed by the dynamics of the system, the displacement of the modulating piston is proportional to the difference between control stick and actuator positions (system error).

Displacement of the slide of the actuator slide valve is accomplished by a single mechanical input. It is therefore necessary to either recombine the three channel signals (modulating piston positions) into a single composite signal by some averaging or summing technique, or to select one signal from among the three. For reasons elaborated elsewhere herein, the latter method was chosen. The signal selection is performed in the voter mechanism. Inputs to the voter mechanism are the angular positions of three arms as determined by the positions of the modulating pistons to which each arm is attached. The output of the voter is a position of the crank which drives the slide valve. The operation is such that the position of the output crank corresponds to that one of the three input positions which is intermediate; thus, the output of the voter will not follow either of the two extreme inputs, but will follow the mid-value signal. A detailed description of the voter is presented later in this paper.

In addition to signal selection, the voter is required to perform a second function necessary to the operation of the system. Need for the additional function results from the fact that portions of the three outside servo loops are common -- that is, the three servo loops are operating in parallel. In general, unless all parts of the three closed loops have precisely the same characteristics, only one of the loops can be closed at one time. That is to say, only one of the loop errors will become less than threshold magnitude at any one time.

This rigidity effect has been one of the stumbling blocks to successful use of channel (rather than component) redundancy in position feedback systems. The voter mechanism provides the point in the system that absorbs the slack required, so that the system errors in the three loops can approach zero simultaneously. The voter mechanism accomplishes the required function by permitting the modulating piston positions to disagree. The differences among the three signals, which are fed back into the summing junctions are just enough to make the three channel errors equal and thus permit the three servo loops to close simultaneously. The necessity for precise matching of components in the three redundant channels has, in effect, been eliminated.

Hydraulic power to the actuator cylinder is controlled by the slide valve. The rate-of-flow of hydraulic fluid is proportional to the displacement of the slide of the valve from the neutral (zero flow) position. Since the rate of displacement of the power cylinder is proportional to the hydraulic flow, and flow is proportional to valve slide position, it is apparent that the velocity at which the actuator drives the control surface will correspond to the position of the voter mechanism; and the position of the modulating pistons can be thought of as system rate. The position of the actuator and control surface is the output of the system. A signal proportional to actuator position is generated in the actuator transducers and fed back to the summing junction, thus closing the outside loop.

VOTER MECHANISM

The voter mechanism is a mechanical signal selector. It continuously selects and transmits a single mechanical position from three different mechanical position inputs. The device consists of three input arms, a torque summing shaft, and an output crank. The arrangement of the mechanism is shown in Figure 5. The inputs to the voter are the angular positions of the three voter arms as determined by the positions of the modulating pistons. The output of the device is the angular position of the torque-summing shaft. The output position is transmitted to the slide of the power-slide valve by the voter output crank rigidly splined on the torque-summing shaft.

Each voter input arm is attached to the shaft by a journal bearing which permits the arm to rotate freely about the shaft. Figure 6 shows the shaft and voter arms prior to assembly. Figure 7 is a sectional view of the voter input arm after assembly onto the shaft, showing the roller cam follower and cantilever spring on the voter arm. A cam detent is machined into the shaft. The spring presses the roller into the cam detent. Upon rotation of the voter arm about the shaft, torque is transmitted to the shaft from the voter arm by the pressure of the roller into the shaft detent. Figure 8 is a graph of the torque transmitted to the summing shaft as a function of the angular displacement of the voter arm with respect to the shaft. The graph shows the detent breakout torque to be 23.7-pound-inches. The slight displacement at breakout is due to the compliance of the voter arm. Because of the shape of the cam, the torque beyond breakout is virtually constant.

The principle of operation of the voter mechanism is more easily explained by making the following two assumptions:

1. The torque on the torque-summing shaft due to bearing friction is negligible.
2. The torque on the shaft due to the loading by the slide valve is small compared to the detent breakout force.

The voter shaft will assume a position of torque equilibrium -- that is, a position for which the summation of torques applied to the voter shaft is zero. Thus:

$$T_1 + T_2 + T_3 + T_L = 0$$

where,

T_1, T_2, and T_3 are the torques applied to the voter shaft by the detent rollers of arm No. 1, arm No. 2, and arm No. 3; and T_L is the load torque of the slide valve.

Figure 9 is a graph of the summing shaft detent characteristic, idealized and greatly expanded. It covers only the region of voter arm displacement within 0.01 radians of detent center. Assume three position inputs to the voter mechanism, such that voter arm No. 1 is displaced by θ_1 radians from detent center, and voter arm No. 2 is displaced by θ_2 radians. The length of the vertical arrows on (Figure 9) represent the magnitudes of the torques, T_1 and T_2, applied to the voter shaft by voter arms No. 1 and No. 2. If $T_1 = T_2$, the condition of torque equilibrium can be satisfied only if $T_3 = T_L$ (that is, when the torque from voter arm No. 3 is equal to the load torque). It is evident that the position of the summing shaft detent center will be displaced by θ_3 from T_3, and that θ_3 is proportional to T_L. Further, as long as $T_1 = T_2$, θ_3 is independent of θ_1 and θ_2. Since θ_3 is very small, it is evident that the position of the voter shaft will be the position of the mid-position voter arm, and independent of the positions of the other two voter arms.

The operation of the voter mechanism will, of course, be modified by torques due to the dynamics of the masses of the shaft, output crank, and valve slide, and by torques due to friction in the voter arm bearings. During operation of the flight control system, the voter arm detent rollers will, in general, be continually moving. Control of the voter output position will pass from one arm to another as their relative positions change.

MODULATING PISTONS

Each output of the three redundant signal channels is the position of a modulating piston. Operation of the voter mechanism and slide valve requires a mechanical position signal at high-force levels. This signal is provided by the modulating piston operating from the pressure provided by its respective electrohydraulic servo valve. The modulating piston assembly consists of a cylinder housing, a piston, and a position transducer. The voter arm of the voter mechanism connects to the middle of the modulating piston as shown in (Figure 5). The piston has an area of 0.306 inches and an operating stroke of plus or minus 0.3 inches. The piston is capable of forces in the order of several hundred pounds. Because the modulating piston force into the voter arm is so much higher than the voter detent force, the signal into the voter may be considered as pure position.

ELECTROHYDRAULIC SERVO VALVES

Each signal channel terminates in an electrohydraulic servo valve at the servo actuator assembly. These valves are single stage -- that is, each consists of an electric torque motor and a hydraulic amplifier, but does not have the second-stage spool and sleeve of the conventional two-stage valve. The modulating piston can be thought of as replacing the second-stage spool except for one major difference. The position of the modulating piston is fed back electrically, rather than mechanically, as is the position of the second stage spool fed back in two stage valves. The valve on the breadboard model consisted of a fluidic amplifier driven by a dc torque motor.

The torque motor has two armature windings. Each winding has a dc resistance of 1000 ohms and an inductance of 5 henrys. Full valve flow is produced by either 12 milliamperes flowing in one of the windings or by 6 milliamperes flowing in both. On the breadboard model, these windings were operated in parallel from a current amplifier output of the servo amplifier. This scheme provides dual redundancy in each torque motor.

The maximum flow of the electrohydraulic servo valve was not high enough to achieve the full-response of the Fly-By-Wire system. A flow rating of double that of the existing valve would better match the area and stroke of the modulating pistons.

POSITION FEEDBACK

The basis for design of the Fly-By-Wire system is the closed-loop concept of the feedback control system. In such a system, the output position is fed back to the input and compared to the commanded position. A signal proportional to the difference between the input and output positions is caused to be converted, and amplified to a power level sufficiently high to drive the actuator at the output of the system. As compared to open-loop designs, closed-loop techniques make the output position of the system substantially independent of the gains of all converter and amplifier devices between the point of comparison (of the input and output positions) and the output actuator. Further, by use of specific design techniques, the output position of a closed-loop control system can be virtually unaffected by variations in the power supplies.

The precision of control possible in feedback systems is limited only by the gain of the forward part of the control loop. High-gain systems have the desirable characteristic of fast response to input commands, and a stiffness, which cannot be achieved in open-loop systems. These control characteristics are lacking in conventional mechanical flight control systems, largely because the linkage (cables, rods, cranks, etc.) between the pilot's control stick and the control surface power mechanism are operating open loop.

With all these advantages over open-loop systems, why aren't all systems closed loop? The answer is: Reliability; the open-loop system is inherently more reliable. Open-loop systems have fewer failures; when failures occur they are less often hardover failures than in feedback systems. Loss of feedback invariably results in an error signal of saturation magnitude, and the high gain of the forward loop amplifies the error into an uncontrolled hardover at the control surface.

The Fly-By-Wire system employs redundancy techniques to bring the reliability of the feedback flight control system up to an acceptable level. However, control of a single-power actuator from multiple signal channels presents some major design problems. These problems arise from the fact that two or more position feedback systems cannot operate in parallel. Another way of stating the same thing is: if two closed-loop servo systems operate in parallel, their common output is a summation of forces, not positions. These problems do not arise in the design of multiple channel systems in which each channel controls a separate output actuator, and position feedback signals can be independent of each other. Reasons for adopting electrical feed, rather than mechanical feedback, for the present system are discussed in the following paragraphs.

MECHANICAL FEEDBACK

A Fly-By-Wire system designed around a mechanical feedback system would be quite different from the present system. The configuration would be two servo loops in cascade: a control servo loop in which the output would be the modulating piston position, and a power loop in which the actuator output would position the control surface. The control loop output would be the power loop input. Whereas the present system, using electrical feedback, has one servo loop within the others; the mechanical feedback system would have one loop following the other.

During design of the present system, it was recognized that if the actuator loop were closed back into the slide valve input, some design problems would be simplified. For this reason, a study was made to determine the feasibility of incorporating a mechanical feedback linkage into the servo actuator. The proposed feedback linkage was a differential level which accepted input displacements from the modulating piston and the actuator position and drove the slide of the power valve with the difference between the two displacements. The study revealed that the open-loop gain of the closed-loop actuator system would be in direct proportion to the ratio of the level arms of the feedback linkage, and that the force required at the summing detents of the voter mechanism would be proportional to the gain. The displacement of the modulating piston, sufficiently large for full displacement of the valve slide, was too small to correspond to full displacement of the actuator. If the modulating piston were designed to have sufficient stroke and force, then the electro-hydraulic servo valve would need to have a flow several times more than any single-stage valve available.

ELECTRICAL FEEDBACK

For the reasons outlined above, the decision was made to use electrical feedback in the design of the system. This decision made possible the generation of multiple feedback signals at the actuator and closing the loop back into the input of each channel. With electrical feedback, the displacement of the modulating piston need only be large enough to correspond to the displacement range of the valve. It should be noted that the feedback technique finally adopted results in the outside loop being closed around parts which are common to the loops of the other two channels for the system. This feature, the parallel operation of three closed-loop systems, is made possible by the installation of the voter mechanism.

POSITION TRANSDUCERS

Definition of the requirements for transducers which generate the electrical signals in a Fly-By-Wire system depends primarily on two considerations: (1) the system design of the flight control system in which the devices will generate the signals, and (2) the state of the art of such devices that are available.

Choice of the type and configuration of the transducers is influenced by the following features of the Fly-By-Wire system design:

1. The system is basically a closed-loop position servomechanism.

2. Position feedback signals are electrical, rather than mechanical.

3. The displacements of the mechanical parts for which position is fed back are translational, rather than rotational.

4. All command and feedback position transducers must be in triplicate, because of the redundant configuration of the system.

The requirements for the feedback transducers are more critical than the requirements for the command transducer. Loss of command signal results in a return-to-neutral command rather than the hardover error signal that results from loss of the feedback signal. Since the positions fed back are due to translational motion, force transducers were eliminated from further consideration, as were rotary synchros, potentiometers, and rotary differential transformers.

From the standpoint of mechanical design, the installation presenting the greatest problems was the control surface actuator position transducer. The control surface actuator consists of a cylinder, a piston, and a long piston rod. The motion of the actuator is plus or minus 1.65 inches. The transducer selected was the type known as the linear variable differential transformer (LVDT). The transducer is designed in a triplicate tandem configuration -- that is, it consists of three complete and independent sets of windings installed concentrically and end-to-end on a long, small-diameter; tubular stator. The armatures of the three transducers are fabricated into a single rod which slides within the tubular stator. The final transducer assembly is approximately 22 inches long and 3/8 inches in diameter. The transducer is installed inside the rod of the actuator. The result is a compact, completely protected, transducer installation. The displacement of the transducer is equal to the actuator displacement. The electrical output of the device is nominally 15 volts per inch of displacement when the excitation is 26 volts at 400 Hz.

The design of the control stick position transducer is identical to that of the control surface actuator transducer, except that the diameter of the stator is increased, to add rigidity, and the rod end is modified for mechanical connection to the crank on the control stick shaft. The control stick transducer assembly is shown in (Figure 3.)

The modulating piston position transducers are three individually operated linear variable differential transformers. Each of the three transducer armatures is coupled to a modulating piston as shown in (Figures 2 and 5.) The stator of the transducers is specially designed to accept a cylindrical metal tube, installed between the armature and the stator, which acts as a seal against loss of hydraulic fluid from the modulating piston sleeve.

The slide valve position transducer is a triple tandem configuration, similar to the actuator and control stick transducers, except that the slide valve transducer is shorter and of larger diameter. Its installation on the slide valve is shown in (Figures 2 and 5.) Each of ;the three transducer sections is electrically similar to the modulating piston transducer, except that, the sensitivity (gain) of the slide valve position transducer is greater by a factor equal to the mechanical advantage of the voter mechanism.

POWER REQUIREMENTS

For reliability reasons, the Fly-By-Wire system should be powered from three independent hydraulic and electric power sources: one hydraulic and one electric power supply for each of three channels in the system. These power sources should be sufficiently independent to prevent a failure in one source from affecting another. It is important that each channel power source be driven by its own prime mover; however, it is desirable from the standpoint of reliability that the hydraulic pump and the electric generator in each channel be driven by the same prime mover, thus reducing to half, the number of prime movers per channel which can cause a channel failure. In a typical aircraft, the prime movers are the aircraft engines. For this reason, multichannel Fly-By-Wire systems are more suited to multiengine aircraft, or to vehicles in which independent sources of power are available.

Electric Power

Each channel in the Fly-By-Wire system operates from standard, aircraft single-phase, alternating current. Voltage and frequency are nominally 115 volts and 400 Hz, respectively.

Actual voltages and frequencies may vary over reasonably wide limits; nothing inherent to the design of the control system dictates close voltage or frequency regulation. The 400 Hz ac, supplied to each channel, furnishes the excitiation to all position transducers in the channel, and the reference voltage to the signal demodulators.

Direct current electrical power is required for the amplifiers, relays, and solenoid-operated hydraulic valves. In an actual airplane installation, all dc voltages for a particular channel would be derived from the 400-Hz ac power supplied to the channel. On the laboratory model, a separate power supply is installed in each channel amplifier package. This installation converts the 115-volt ac into: 26 volts ac for excitation of all the position transducers in the channel; 6 volts ac for the reference voltage to the signal demodulators; and the dc voltage for the electronic amplifiers. Power for operation of relays and solenoid valves is derived from a 28-volt laboratory dc supply.

Hydraulic Power

Hydraulic power can be supplied separately to the electrohydraulic servo valve in each of the three channels, and to each tandem section of the power slide valve and power cylinder. However, the hydraulic power to the laboratory model was supplied from a single source. The hydraulic fluid is the type described in Specification MIL-H-5606. The supply pressure is nominally 3000 psi, and the filtration is 2 microns. Peak loading on the hydraulic supply is 8 gallons per minute.

MONITORING

Operation of the three redundant channels of the system can be conveniently monitored by either of two methods:

1. The output signal of each channel is the position of a modulating piston. Electric signals proportional to the positions of the modulating pistons are available at the outputs of the modulating piston position transducers. These three signals can be compared in a monitor of the majority voting type.

2. The output position of the voter mechanism corresponds to the position of the modulating piston of that channel which carries the mid-value signal. Electrical signals proportional to this mid-value signal are available at the three outputs of the triple-slide valve transducer. The system can be monitored by comparing this mid-value signal with each of the three modulating piston transducer signals.

COMPUTER SIMULATION

Prior to fabrication of the breadboard model, the complete Fly-By-Wire system was simulated on the electronic analog computer. Studies were performed to determine the performance and stability of the system under various failure conditions and at various system gains. As a result of those studies, the power-slide valve was reworked to increase the maximum flow by a factor of 3.0. In addition, the analog computer study resulted in the installation of a set of position transducers on the power slide valve. The computer study indicated that for very high system gains an unstable condition became evident under certain failure conditions; feedback of the slide valve position stabilized the system. This instability could not be duplicated in the actual hardware system because of the system gain limitations imposed by maximum flow rates of the electrohydraulic servo valve and the power-slide valve.

SYSTEM EVALUATION

EVALUATION OF THE LABORATORY MODEL

The laboratory model of the Fly-By-Wire system was evaluated for performance under normal conditions and under various failure conditions. The laboratory test installation Figure 10 consisted of the laboratory model, the test bench with control panel, the hydraulic and electric power supplies, the power control panel, a variable frequency drive, an eight-channel recorder, and electronic test equipment.

System Input Signals

All input signals to the Fly-By-Wire signal channels were introduced by displacement of the control stick shaft, except step inputs during transient response tests, and autopilot signals. Step input signals were introduced by switching 400-Hz voltages from fixed transformer taps. Autopilot signals were introduced as 400-Hz voltages from a Servoscope. Sinusoidal inputs were introduced by means of a variable frequency power drive.

System Instrumentation

The position transducers of the system provided instrumentation for recording of control stick position, control surface actuator position, modulating piston positions, and power slide valve position. Torque motor current was measured at the output resistor of the current amplifier in each channel. All of the above quantities were demodulated, and records were made of their time histories on an eight-channel recorder.

FAILURES OF NONREDUNDANT COMPONENTS

Mechanical parts of the flight control system are, in general, not redundant. The linkages in the control stick assembly, between the stick grip and the tandem control stick transducer rod, are single. None of the mechanical parts of the power mechanism between the voter shaft and the control surface are multiplicated.

In addition, the linkages between the control surface actuator and the position feedback transducer are not redundant. The flight control system is, of course, not fail-operative in the event of breakage or jamming in any of these parts. However, most of these components have shown an extremely high order of reliability in conventional control systems. Metal rods, cranks, brackets, and other rigid parts of the Fly-By-Wire system can be made very compact and, for the most part, can be installed in protective enclosures and may prove to have even higher reliabilities than the long, unprotected cables and linkages of conventional mechanical systems.

At least two of these nonredundant components, however, do not possess the extreme reliability of simpler parts. These components are the power-slide valve and the power cylinder. Although both of these elements are dual tandem, and can continue to operate upon loss of one hydraulic supply, they cannot perform their function if either is jammed.

SINGLE CHANNEL FAILURES

Those components of the Fly-By-Wire system that have the highest probability of failure are installed in triplicate in the three independent signal channels between the pilot's control stick and the power mechanism. The majority of probable failures are in the parts of these three channels. The net result of any of these failures is a false signal at the mechanical output of that channel in which the failure occurs. This mechanical output signal is represented by the position of the channel voter arm as determined by the position of the modulating piston. The false signal will be manifested as a hardover of the voter arm in either direction, as a passive centering of the voter arm, or as any position between these extremes. Following is a partial list of those signals for which the system is fail-operative:

1. Failure of electrical power source.
2. Failure of channel power supply.
3. Primary or secondary winding circuits of control stick transducer, open or shorted.
4. Input circuit to demodulator, open or shorted.
5. Loss of reference voltage to demodulator.
6. Failure of demodulator.
7. Signal-summing junction circuit, shorted or open.
8. Failure of electronic amplifier due to a number of causes.
9. Circuit between amplifier and torque motor winding, open or shorted.
10. Mechanical failure in the single-stage electrohydraulic servo valve.
11. Hydraulic failure of electrohydraulic servo valve due to plugging jet-pipe nozzles.
12. Failure of channel hydraulic power.
13. Electrical circuit to channel solenoid valve, open or shorted.
14. Mechanical failure of channel solenoid valve.
15. Jamming of modulating piston.
16. Mechanical failure of modulating piston spring.
17. Failure of voter arm detent spring or detent roller.
18. Binding of voter arm bearing.
19. Primary or secondary winding circuits of modulating piston position transducer, open or shorted.
20. Primary or secondary winding circuits of surface actuator position transducer, open or shorted.

FAILURE SIMULATION

In order to make possible the evaluation of the effects of all channel failures on the performance of the system, a smaller group of simulated failures was set up that duplicates the effect of the actual failures. For purposes of the evaluation testing, the effect of any one of the numerous possible failures which can occur in the three redundant channels can be approximated by applying one or more of the following conditions to any one of the channels:

1. Introduction of a hardover signal -- that is, a step electrical signal large enough to represent a large displacement of the control surface.
2. Opening of the actuator position feedback signal circuit.
3. Reduction of the hydraulic supply pressure to one-half normal pressure and to zero.
4. Variation of amplifier gain to one-half normal and to double normal gain.
5. Variation of electrical supply voltage.
6. Disengagement of voter arm detent.

DEFINITION OF NORMAL CONDITIONS

For purposes of the discussion of the evaluation of the performance of the laboratory model, normal conditions are defined in the following paragraphs.

Component Failures

All component parts are functioning and no part has failed.

Electric Power

Nominal voltage and frequency are 115 volts and 400 Hz. Electric power is applied synchronously to all three channels of the control system.

Hydraulic Power

Nominal system pressure is 3000 psi. Nominal pressure is applied to all three electrohydraulic servo valves and to each of the two cylinders of the tandem actuator through the tandem power-slide valve.

Control Surface Position

Normal position of the surface is zero degrees.

Amplitude

Normal amplitude of surface displacement is ± 5 percent of total surface displacement range. Actual maximum surface displacement range on the laboratory model is ± 30 degrees.

Amplifier Gain

The normal gain of the amplifier in each channel is 33 milliamperes per volt.

Surface Actuator Loading

For convenience, the normal surface actuator loading is defined as no load. The simulated surface loading is shown in Figure 11.

PERFORMANCE UNDER MANUAL CONTROL

Evaluation of the performance of the Fly-By-Wire system under manual control was made by observation of the response of the control surface to movement of the pilot's control stick by a human operator. Reaction to the operator's stick force is furnished by a centering spring and damper installed on the control stick shaft. Response of the surface to stick movement was judged to be faster than that of mechanical control systems. Resolution was particularly good; the surface responded to any perceptible movement of the stick, however small.

Large and fast motion of the stick results in noticeable phase lag of the surface and some feeling of detachment by the operator. However, both of these effects are largely determined by the feel system characteristics, and to a lesser extent by response of the system. During the evaluation, various conditions and failures were imposed on the system. These conditions included: introduction of hardover signals in one channel, interruption of the actuator position feedback circuit in one channel, interruption of the control stick input circuit in one channel to one-half of normal pressure and to zero pressure. Instantaneous application of any of these failures was undetectable to the operator, or was detected with difficulty.

The magnitude of the effect of a single-channel failure is largely determined by the control surface displacement existing at the time of failure, and the relative linearity of the three channel signals generated at the control stick transducer and at the surface actuator transducer.

Adequate control of the system is maintained by the operator, under single failure conditions, both prior to and after deactivation of the failed channel. However, introduction of a second failure into one of the unfailed channels prior to deactivation of the first failed channel resulted in a strong transient displacement of the surface, noticeable degradation of control, and, for some failures, complete loss of control.

Performance of the system for two-channel and one-channel operation was evaluated by disengaging the voter arm input of one channel or two channels, thus eliminating any degradation effect of the failed channel. The unused channel is disengaged by installation of a wedge block on the voter arm, which raises the roller free of the shaft detent. Response of the system to manual control with one channel and two channels thus disengaged was not noticeably different from that of the normal three-channel system.

SYSTEM RESPONSE

Performance of the laboratory model, as indicated by the results of the frequency response and transient response tests, correlates quite closely to that predicted by the analog computer simulated system. Some of the parameters of the actual hardware system were not identical to those mechanized on the simulated system. These parameters include friction in the voter mechanism, outside loop gain, and slide-valve position feedback.

The friction in the voter mechanism is in the journal bearings of each voter arm input. The value of the frictional force in the bearing can be as high as one-third of the torque generated in the detent by a single voter arm.

The gain of the outside loop (that is, the loop gain including the actuator position feedback) in the simulated system was not achieved in the actual hardware system because of flow limiting in the electrohydraulic servo valve.

Use of the slide-valve position feedback (in addition to the modulating position feedback) resulted in an increase in the stability of the computer simulated system, during two-channel operation. However, the stabilizing effect on the stability of the actual hardware system, with one channel deactivated, was not noticeably greater than the effect of the modulating piston position feedback alone. The difference in the effects of this feedback on the two systems is apparently due to the friction of the voter mechanism and to other nonlinearities in the actual hardware which were not predicted for incorporation into the simulated system.

Frequency Response

The laboratory model was evaluated for response to sinusoidal inputs at frequencies from 0.5 Hz to 20 Hz. The tests were performed on the system operating under representative conditions of loading, amplitude, power supply variations, output position, component failure, and amplifier gain. The inputs to the system were sinusoidal, angular displacements applied directly to the pilot's control stick shaft from a variable frequency power drive. The resulting time histories of the system were recorded on a high-response, eight-channel recorder. Representative data have been selected from numerous frequency response runs and consolidated into graphs and tables to describe the response characteristics of the system.

Normal System Frequency Response

This Fly-By-Wire system cannot be closely approximated by a first- or second-order system because it has inherent nonlinearities. The criterion usually applied to a first-order system is that a phase lag of 45 degrees occurs at the same frequency for which the amplitude ratio is down 3 dB. The criterion for bandwidth in nonlinear systems is quite arbitrary. For the Fly-By-Wire system, application of phase lag criteria results in the most conservative bandwidth. The frequency at which the control-surface actuator lags the control stick, in the normal system operating at small amplitude, is 5.5 Hz, whereas the amplitude ratio is down 3 dB at 9.8 Hz. The bandwidth data from the frequency response tests have been consolidated into a summary that lists bandwidth according to the four most commonly accepted criteria:

1. Attentuation of amplitude ratio by 3 dB.
2. Phase lag of 45 degrees.
3. Phase lag of 90 degrees.
4. Breakpoint frequency.

This summary of bandwidth data is presented in Table 1. The table lists the four criteria frequencies for five amplitudes of system displacements ranging from 5 to 75 degrees. The following observations from the data in the bandwidth table are of interest:

1. The phase lag for which the amplitude ratio is down 3 dB remains consistently near 150 degrees regardless of amplitude.
2. Virtually no attenuation of amplitude ratio occurs at frequencies lower than the frequency at which the phase lag is 90 degrees.
3. The parameter having greatest effect on bandwidth is amplitude. Figure 12 shows the variation of bandwidth as a function of amplitude for three of the criteria discussed above.

Frequency Response Under Various Conditions

The effects, on frequency response, of various conditions of actuator loading, hydraulic supply pressure, electrical supply voltage, surface position, amplifier gain, and selected combinations of these conditions are shown in Figures 13 through 20. These curves of amplitude ratio and phase lag, as a function of frequency, are derived directly from the data of frequency response runs performed on the laboratory model. Figure 13 shows the response of the normal system. Figures 14, 15 and 16 are curves of the response of the system with abnormal conditions imposed as stated, superimposed on the response curve of the normal system (shown in dashed line) for comparison. The following observations on the effects of various conditions can be drawn from the frequency response test data.

1. A sharp rate of change in phase angle occurs at the break point frequency, see (Figure 12.)

TABLE I. BANDWIDTH DATA

SYSTEM BANDWIDTH ACCORDING TO VARIOUS CRITERIA

AMPLITUDE (PERCENT)	FREQUENCY (Hz)	AMPLITUDE RATIO (dB)	PHASE LAG (DEGREES)
±5	9.8 5.5 7.8 8.0	−3.0 0 0.5 1.0*	148 45 90 100
±12	5.1 3.3 3.7 4.2	−3.0 0 0.5 0*	158 45 90 140
±25	3.8 2.75 2.80 3.0	−3.0 0 0.5 0*	155 45 90 135
±50	2.5 1.65 1.80 2.1	−3.0 0 0 −0.2*	140 45 90 125
±75	1.8 1.23 1.40 1.45	−3.0 0 −0.5 −0.7*	125 45 90 98

*AT BREAK POINT

2. Loading of the actuator produces no appreciable degradation of frequency response, see Figure 14.

3. Effect of amplitude on amplitude ratio attenuation and phase lag is pronounced. See Figures 15 and 16. These effects were predicted by the computer simulated system.

Effects of Single Failures

The effect of failure, or partial failure, of components in one of the three redundant channels is shown by the amplitude ratio and phase angle curves of Figures 17, 18 and 19. These curves are superimposed over the curves of the normal system for comparison.

1. The effects of an open actuator position feedback are shown by the curves of Figure 17. The system frequency at 45 degrees phase lag has been reduced to 4.5 Hz for the loaded actuator condition.

2. The effects on response of complete loss of hydraulic pressure in one channel is shown in Figure 18.

3. The effect of disengaging the failed channel from the voter is shown in Figure 19. These curves are actually the frequency response of a two-channel system.

Two-Failure Operation

If a second channel of the system fails before the first failed channel is deactivated, the operation of the remaining system depends on the types of failures. For two hardover failures in the same direction, the surface will be driven hardover, unless one of the failed channels is deactivated. However, the pilot has adequate control of the surface when the two failures are hardover in opposite directions. The response of the system with two opposite hardover failures is shown on Figure 20.

Transient Response

The time required for the output of the system to respond to a step input is determined primarily by two factors: the time required by the command system to drive the power valve slide to the fully open position, and the flow rate of the power-slide valve when fully open. The maximum velocity of the control surface actuator for a fully open slide valve, at a system pressure of 3000 psi, is nearly 10 inches per second. This velocity is not realized during step inputs of less than approximately 25 percent amplitude. Transient response tests were performed by introduction of step ac voltages into the control stick demodulators.

Small Transients

The variation of electronic amplifier gain has secondary effects on transient response to small amplitude step inputs. These effects can be seen in the transient response curves show . in Figure 21. These curves illustrate time delay contributed by each part of the system during the transient. The time required for transmission of the command signal to the torque motor windings can be considered negligible. The time required to establish full current in the torque motor windings is appreciable, but small, and is somewhat affected by the amplifier gain. The high effective source impedance of the current amplifier minimizes the effect of the inductance of the torque motor windings. The largest contribution to the total time is the time required for displacement of the modulating piston. Since motion of the power valve slide is proportional to motion of the modulating piston, the valve reaches only 10 percent of its fully open position during a transient of 5 percent amplitude. This response limitation is due primarily to the inability of the single-stage electrohydraulic servo valve to furnish the hydraulic flow rate required by the displacement of the modulating piston for fast response.

The principal effect of variation of amplifier gain is upon the response time and stability of the current (and consequently torque) in the torque motor control windings.

Large Transients

The maximum velocity of the system is not realized for step inputs of less than 25 percent amplitude. The slide valve does not reach the full-flow position during lesser transients. Response to a 50 percent amplitude step input is shown in Figure 22. Maximum velocity of the system is represented by the slope of the transient curve at approximately the 25 percent amplitude point. It is apparent from the curve that about 40 percent of the response time is required for acceleration of the control surface actuator from zero to maximum velocity. That period corresponds to the opening of the slide valve by the modulating piston acting through the voter and represents maximum velocity of the modulating piston. A corresponding period of time is required for the slide valve to close when the system output actuator approaches the commanded position. The result is an over-shoot of approximately 8 percent amplitude.

CONCLUSION

The program described in this report has resulted in the evaluation of design techniques that offer the potential of significant improvement in reliability and performance over currently proposed designs of flight control systems for advanced aircraft. A laboratory model of a single-axis Fly-By-Wire system was designed and fabricated, and an evaluation of the performance of the model was completed. The model efficiently and reliably enables the pilot to electrically control the hydraulic power mechanism that drives a single aerodynamic control surface.

Feasibility of the design techniques evaluated during the program has been demonstrated. Demonstration of the feasibility of the redundancy techniques are particularly significant. The hardware model represents the successful use of devices that make possible the simultaneous operation of three closed-loop, feedback control systems having mechanical and hydraulic parts common to all three systems. The model has successfully demonstrated that a single pilot's flight command signal can be converted into three signals, transmitted electrically over three independent channels (each of which has a mechanical output), and reconverted by a method of continuous voting into a single mechanical signal. Use of this continuous voting principle is expected to offer a higher potential for improvement of the reliability of Fly-By-Wire Systems than other published redundancy techniques.

Performance of the Fly-By-Wire system after occurrence of a single electrical failure surpassed the objective established for a fail-operative system. Adequate performance was demonstrated upon introduction of a hardover signal, and upon complete loss of electric power, hydraulic power, or actuator position feedback in any one of the three channels of the system.

A passive system results from occurrence of a second failure, provided that the first failed channel is deactivated by either the monitor or the operator. The testing revealed the advantage, inherent to the system, that the first failed channel is not required to be immediately deactivated to meet the fail-operative objective, but needs only to be removed from the system prior to occurrence of the second failure. Further, if the channel location of the first failure is reported to the operator, he can be sufficiently informed upon occurrence of a second failure to make a judgment as to which of the channels remains normal; and using the unfailed channel, he can return to base safely.

REFERENCES

1. E. F. Milier and J. E. Emfinger. Fly-By-Wire Techniques. AFFDL-TR-67-53, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, July 1967.

2. V. C. Sethre, et al. Design Techniques and Laboratory Development of an Electrical Primary Flight Control System. ASD-TDR-62-46, Flight Control Laboratory, Wright-Patterson Air Force Base, Ohio, April 1962.

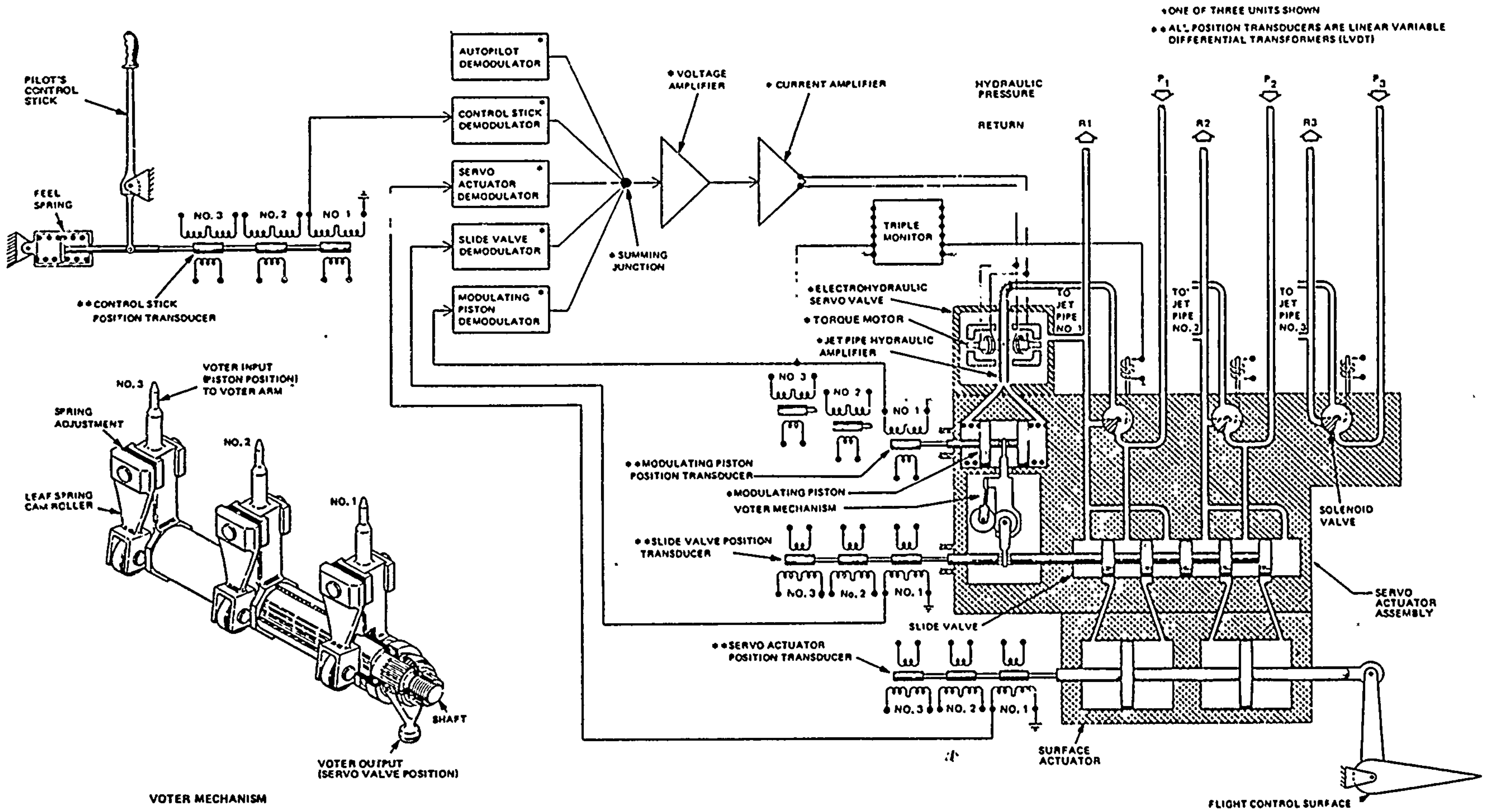

FIGURE 1. FLY-BY-WIRE SYSTEM SCHEMATIC DIAGRAM

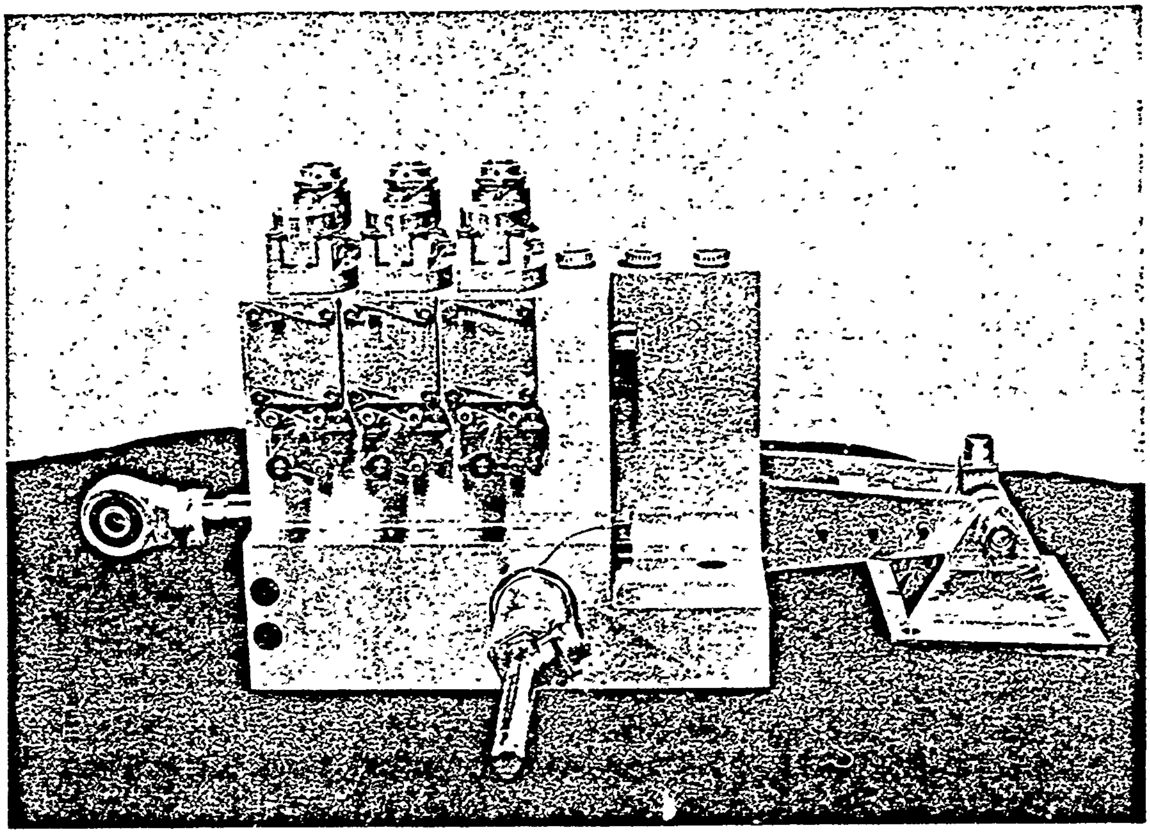

FIGURE 2. SERVO ACTUATOR ASSEMBLY – TRANSDUCER SIDE

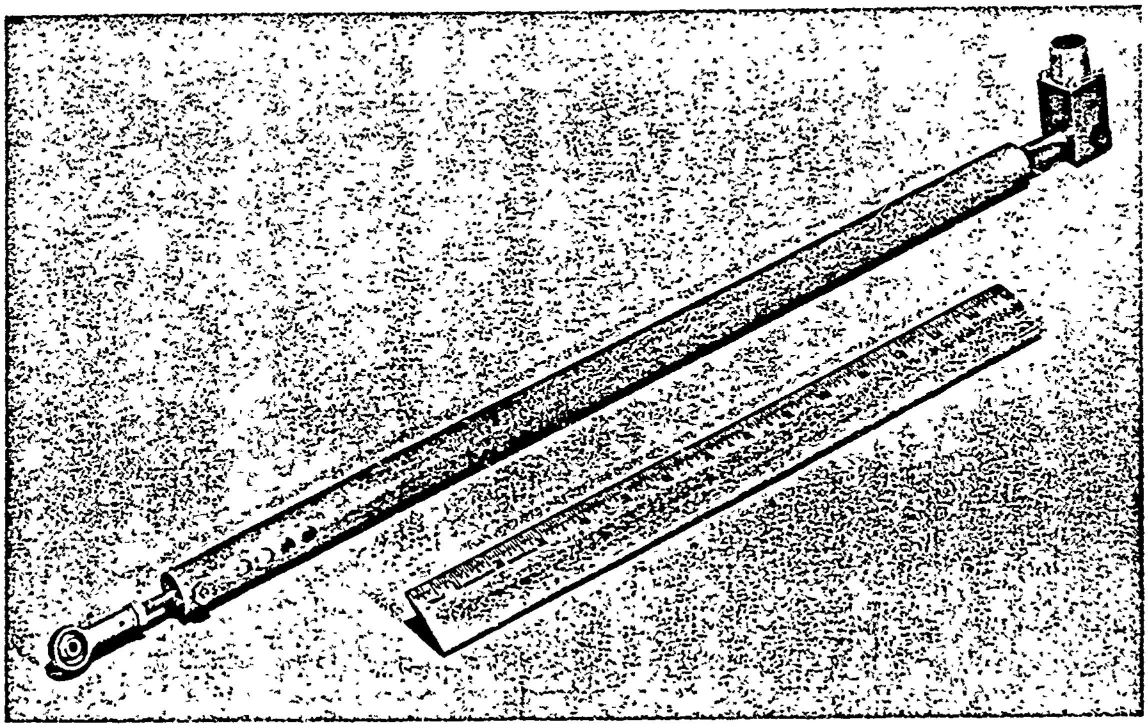

FIGURE 3. . CONTROL STICK TRANSDUCER ASSEMBLY

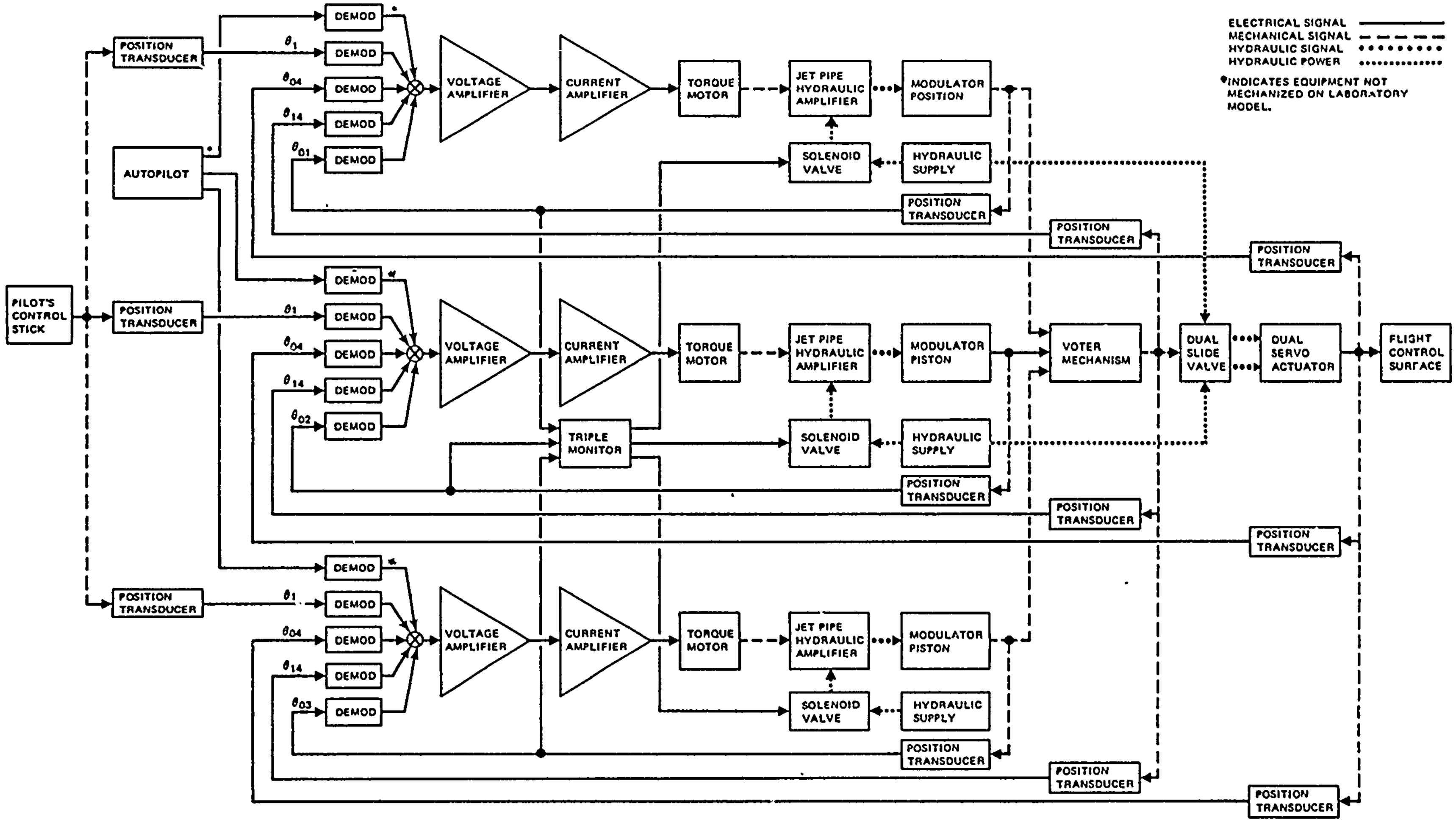

FIGURE 4. FLY-BY-WIRE SYSTEM BLOCK DIAGRAM

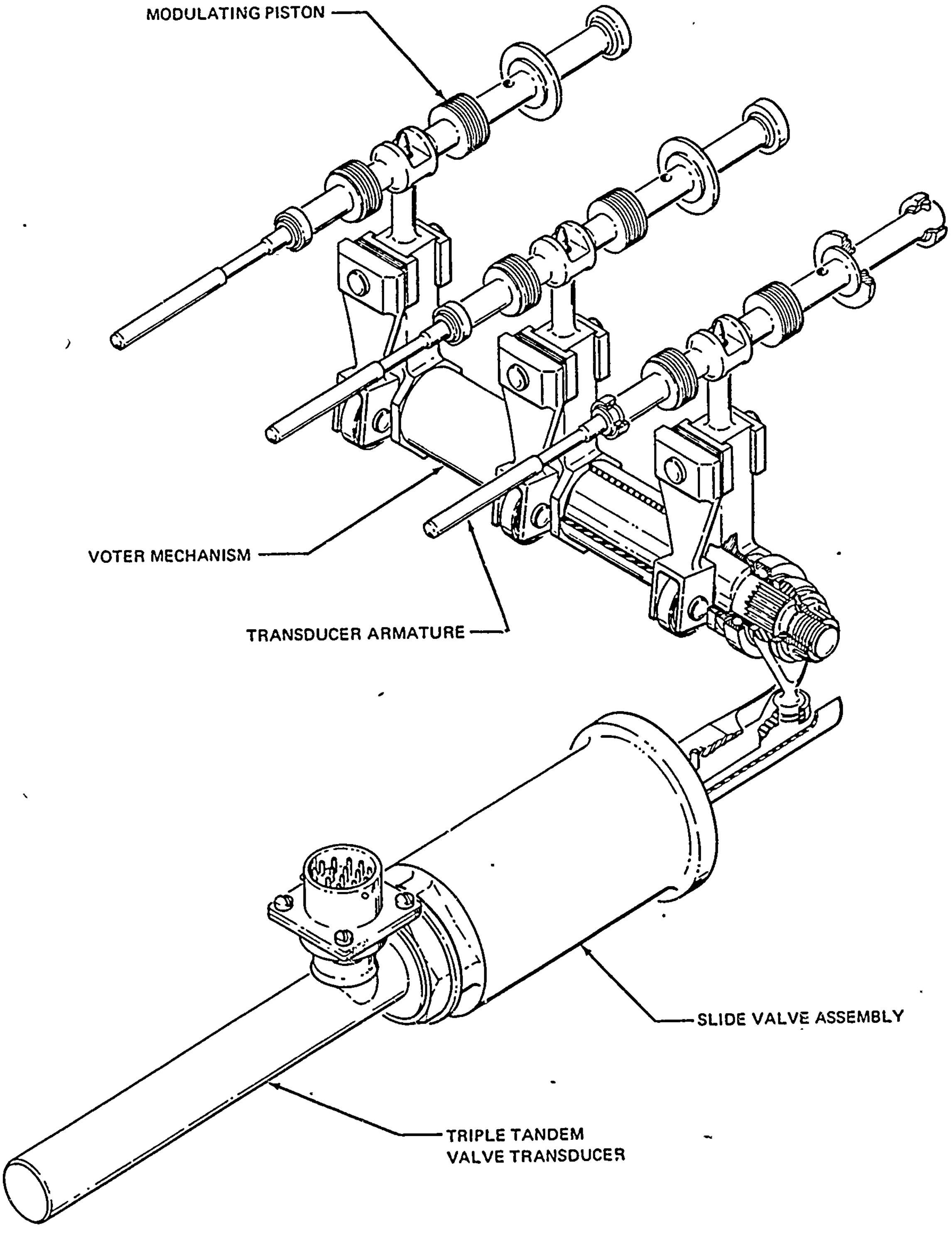

FIGURE 5. VOTER MECHANISM ARRANGEMENT

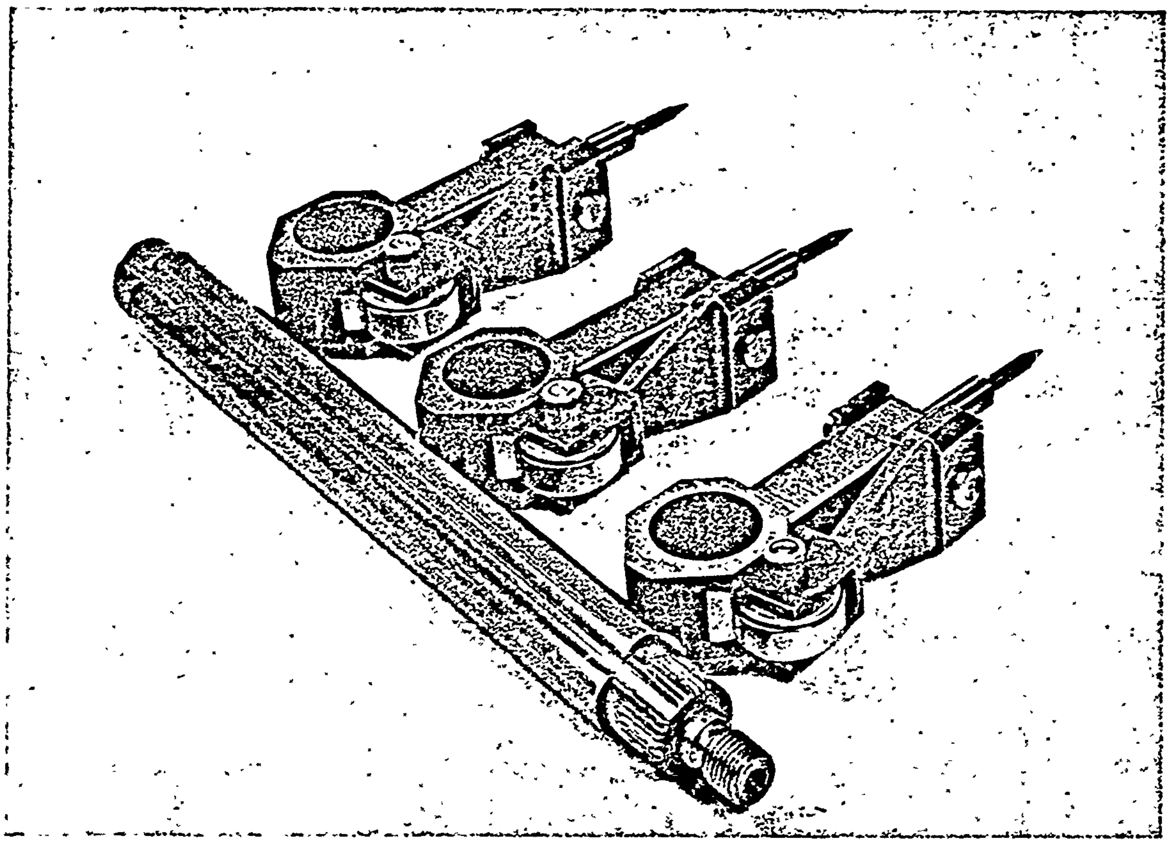

FIGURE 6. VOTER MECHANISM COMPONENTS

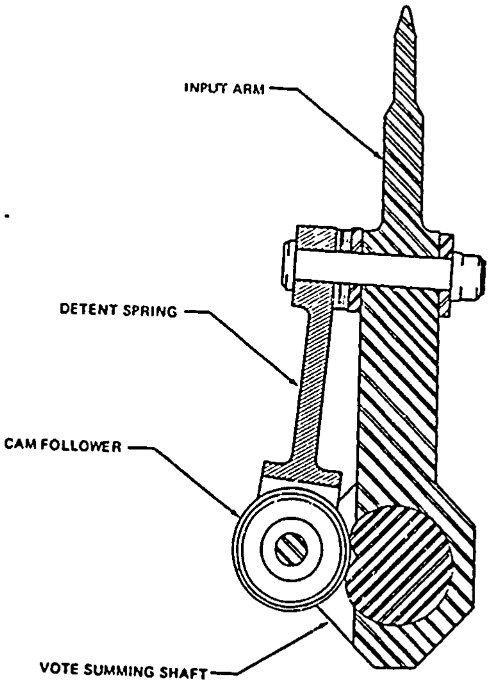

FIGURE 7. VOTER MECHANISM INPUT ARM

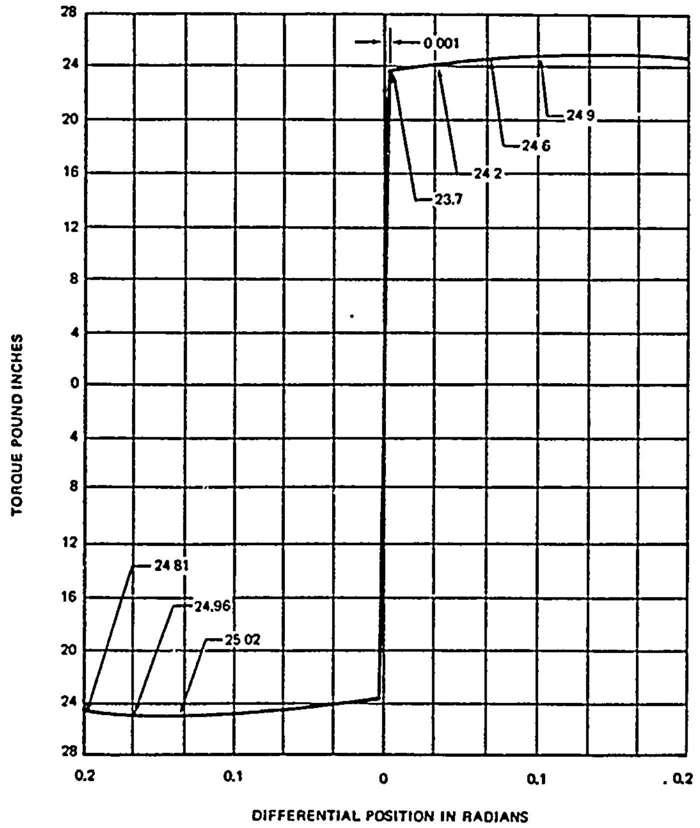

FIGURE 8. VOTER MECHANISM – DETENT TORQUE CHARACTERISTICS

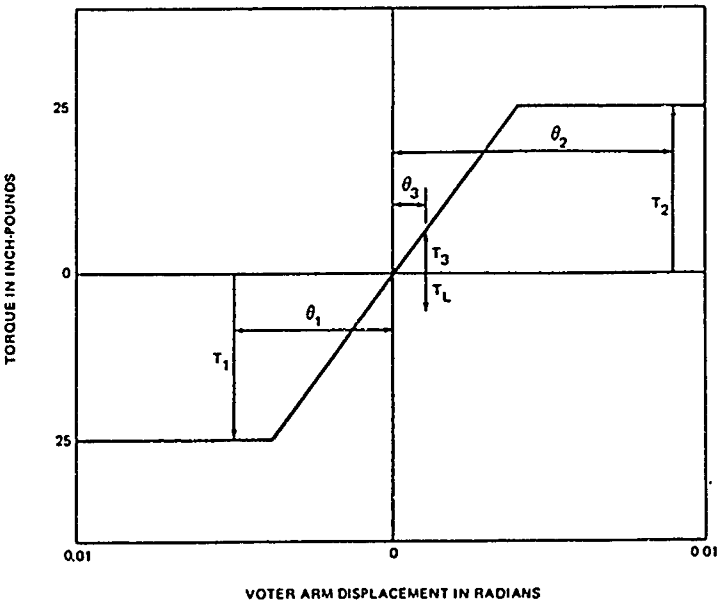

FIGURE 9. VOTER OPERATION

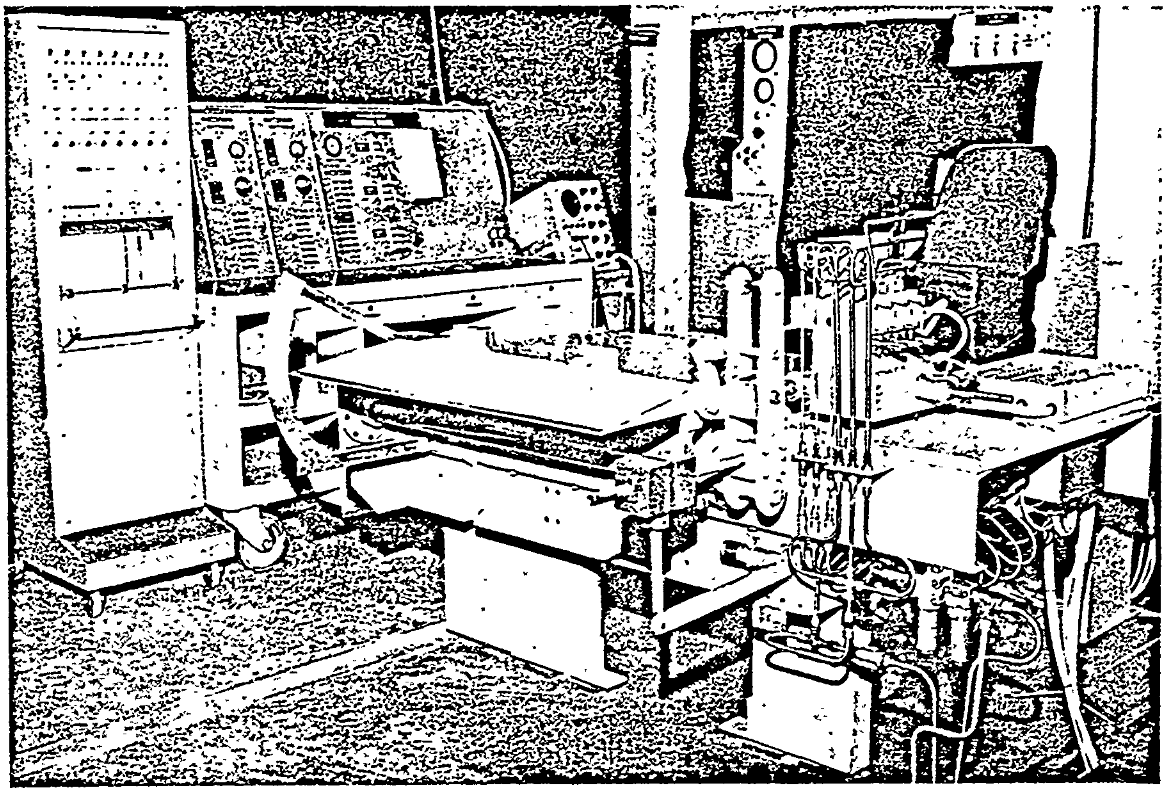

FIGURE 10. FLY-BY-WIRE SYSTEM – LABORATORY INSTALLATION

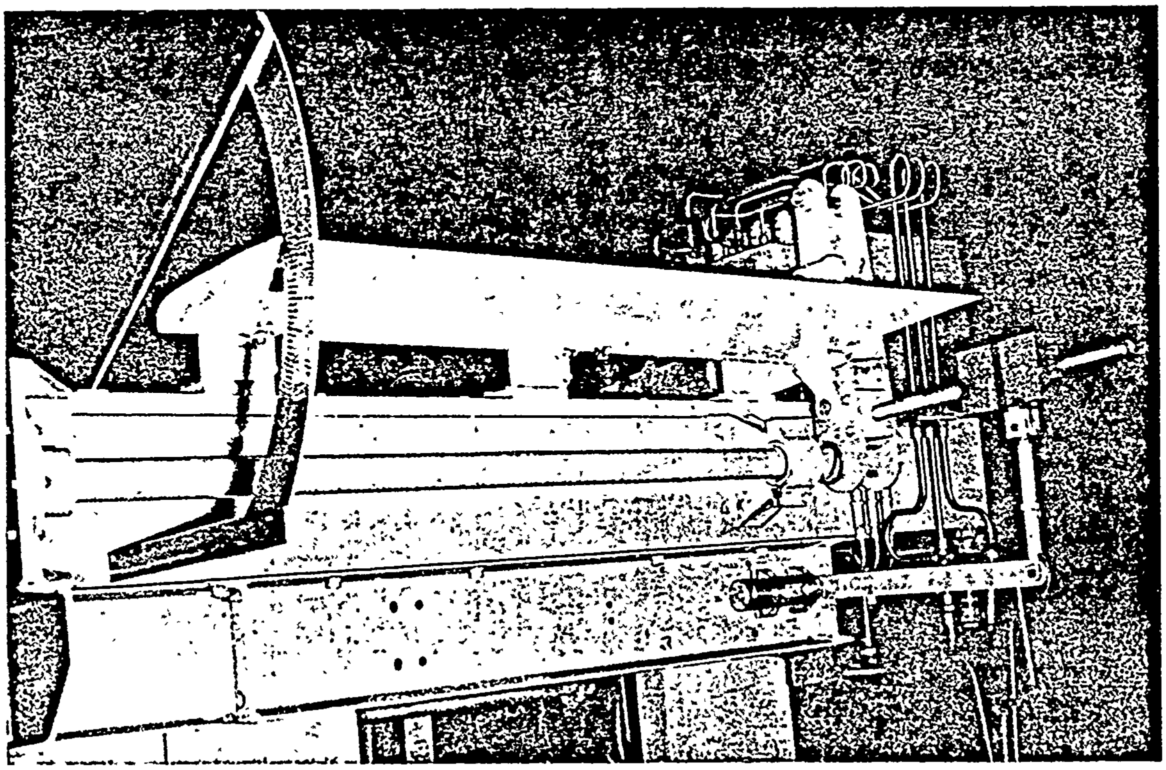

FIGURE 11. SIMULATED SURFACE AND AIR LOAD

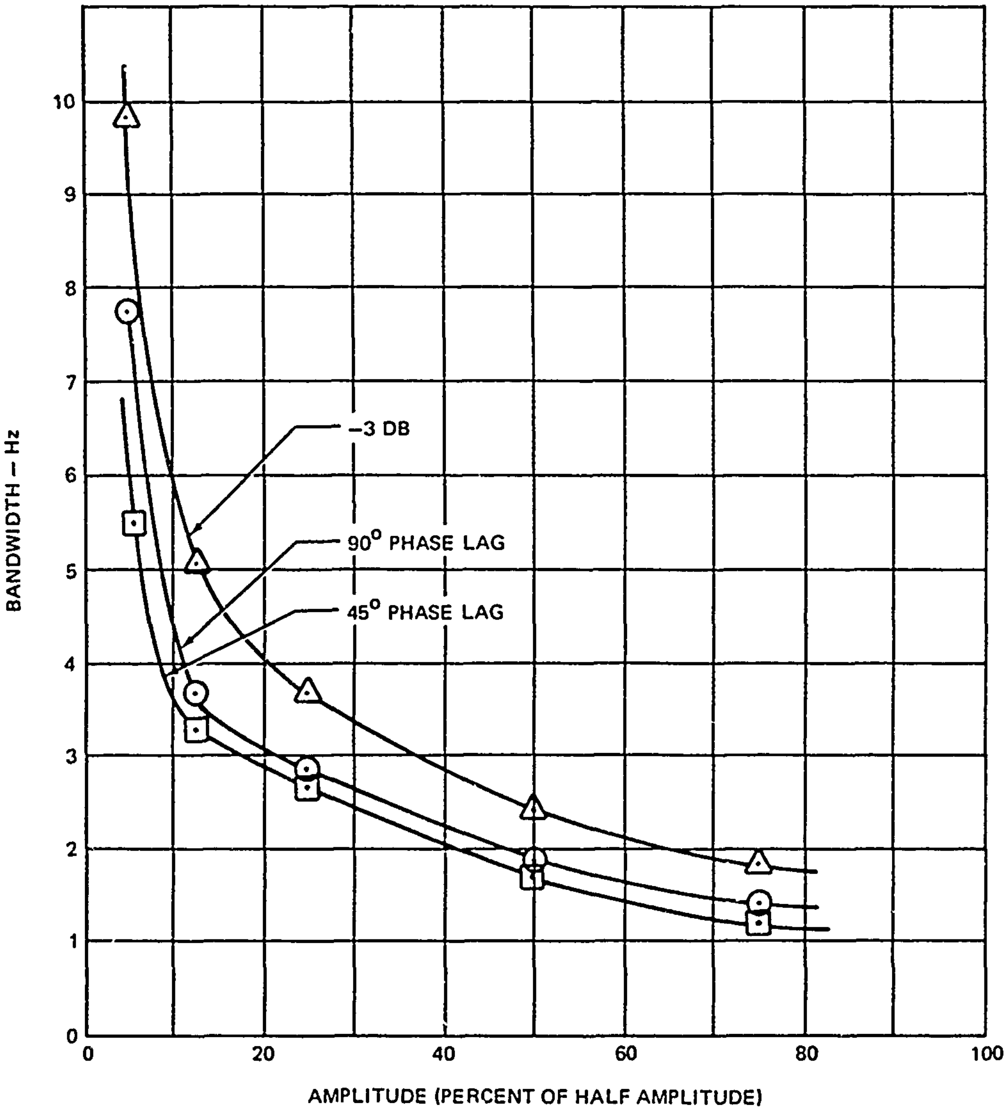

FIGURE 12. EFFECT OF AMPLITUDE ON BANDWIDTH

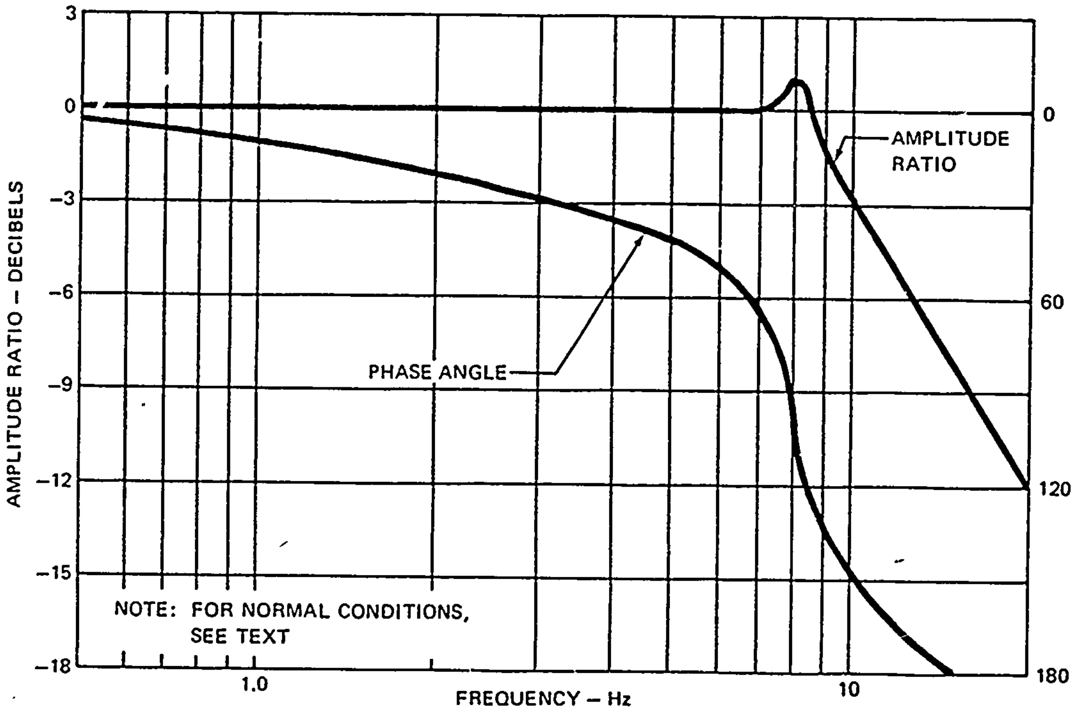

FIGURE 13. FREQUENCY RESPONSE – NORMAL CONDITIONS

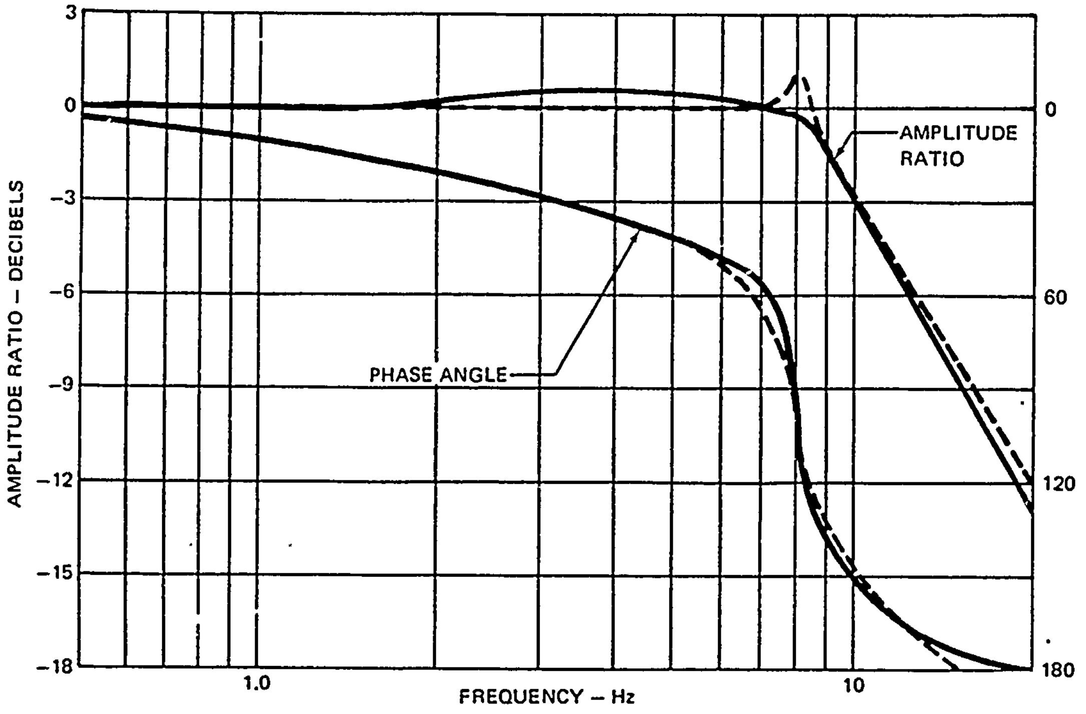

FIGURE 14. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: WITH LOAD

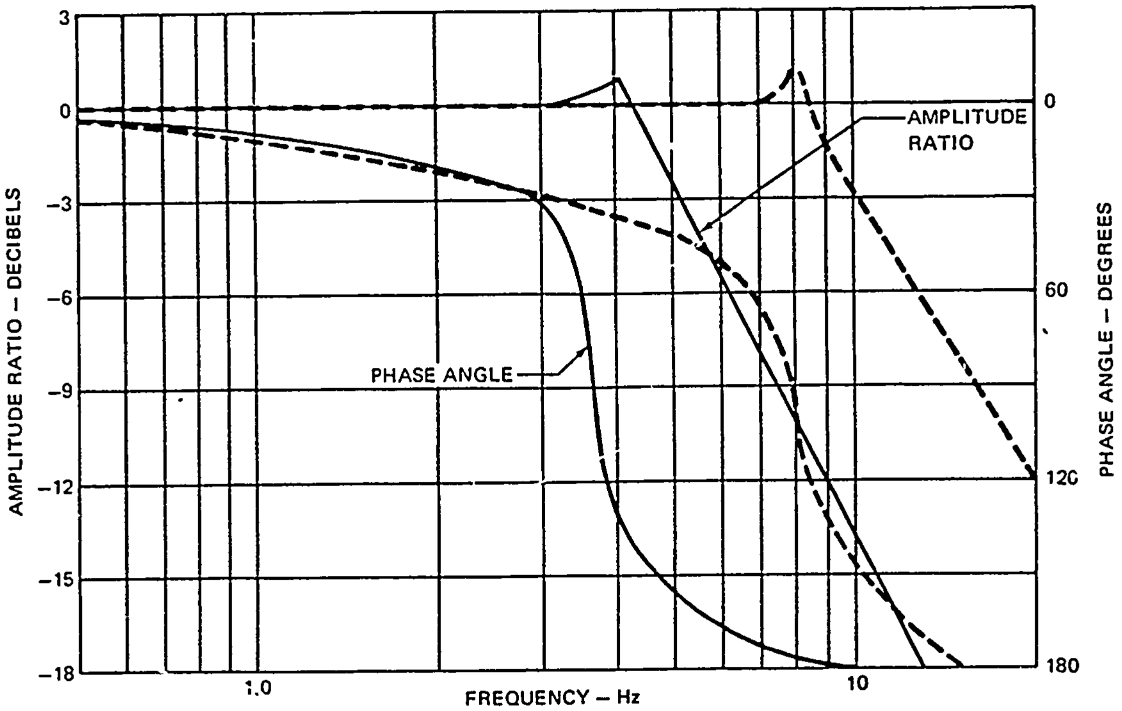

FIGURE 15. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: WITH LOAD AND ±12% AMPLITUDE

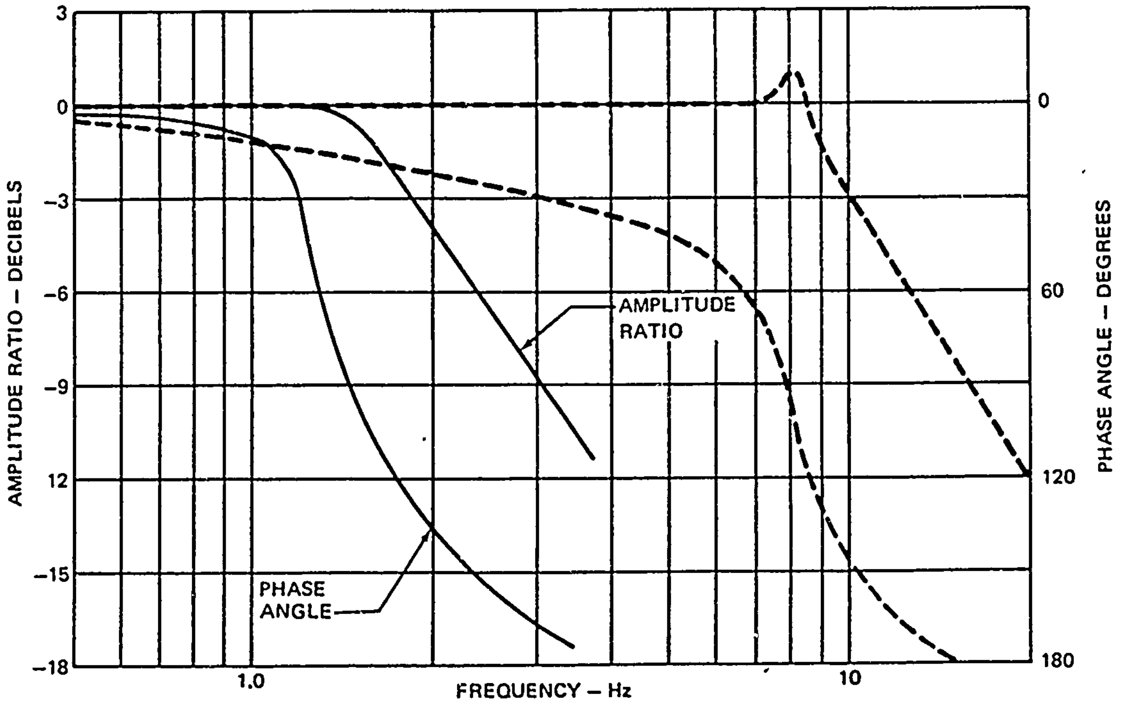

FIGURE 16. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: ±75% AMPLITUDE

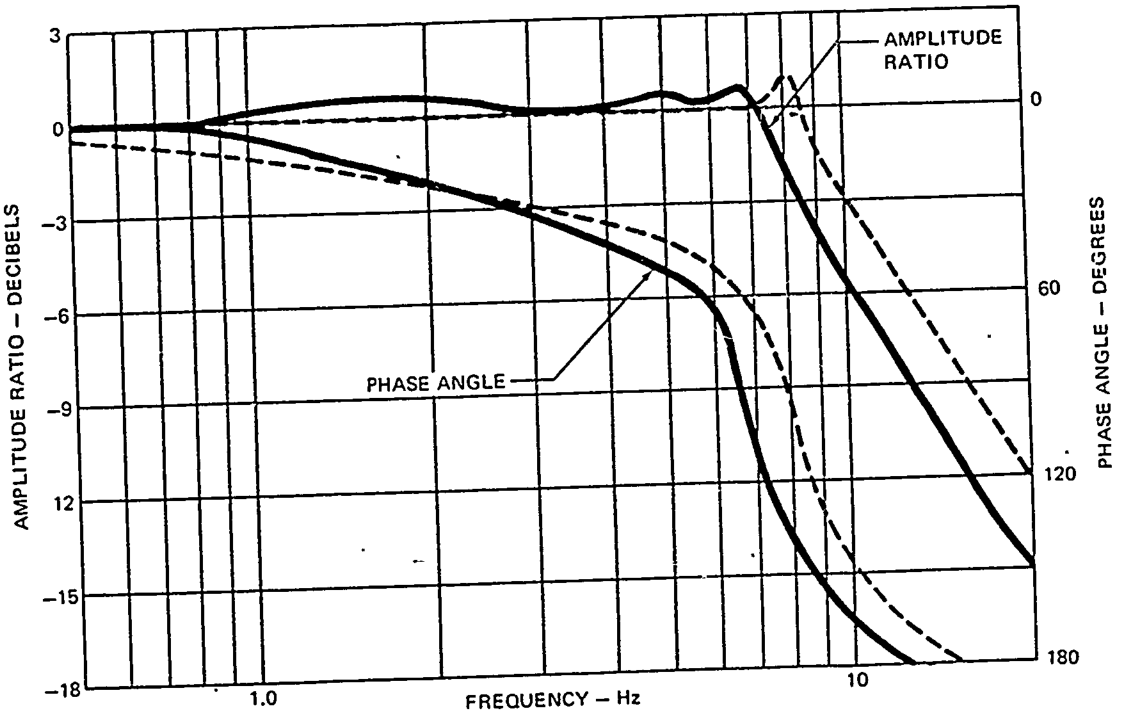

FIGURE 17. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: WITH CHANNEL 1 ACTUATOR POSITION FEEDBACK OPEN, AND WITH LOAD

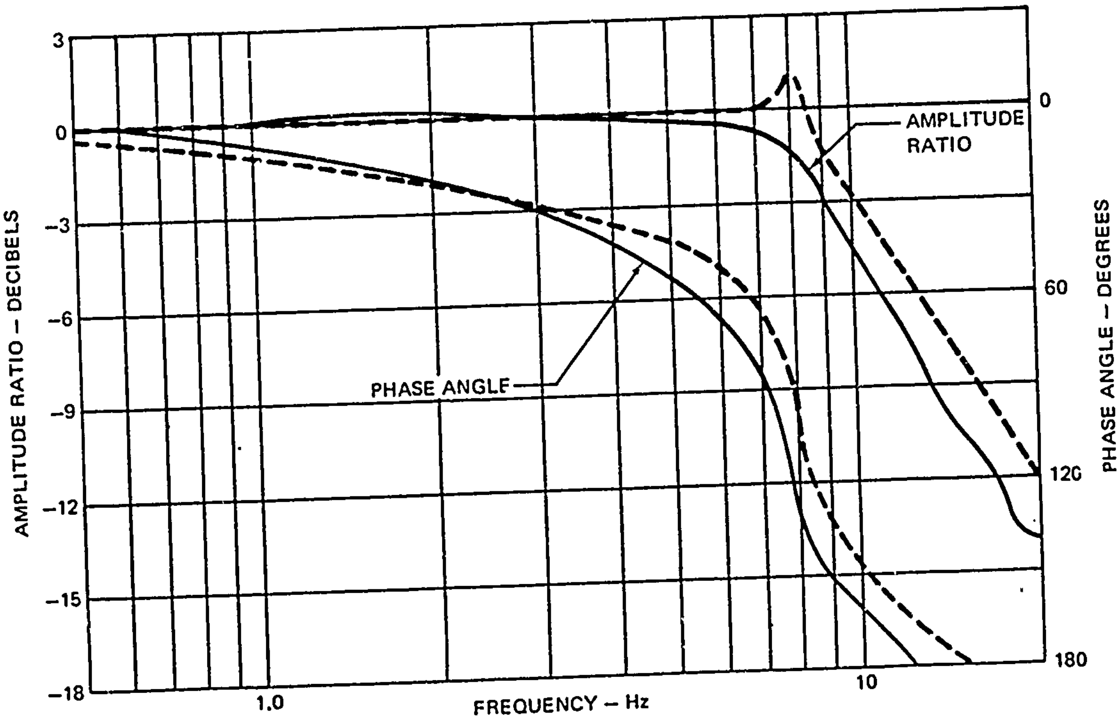

FIGURE 18. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: CHANNEL 1 PRESSURE OFF

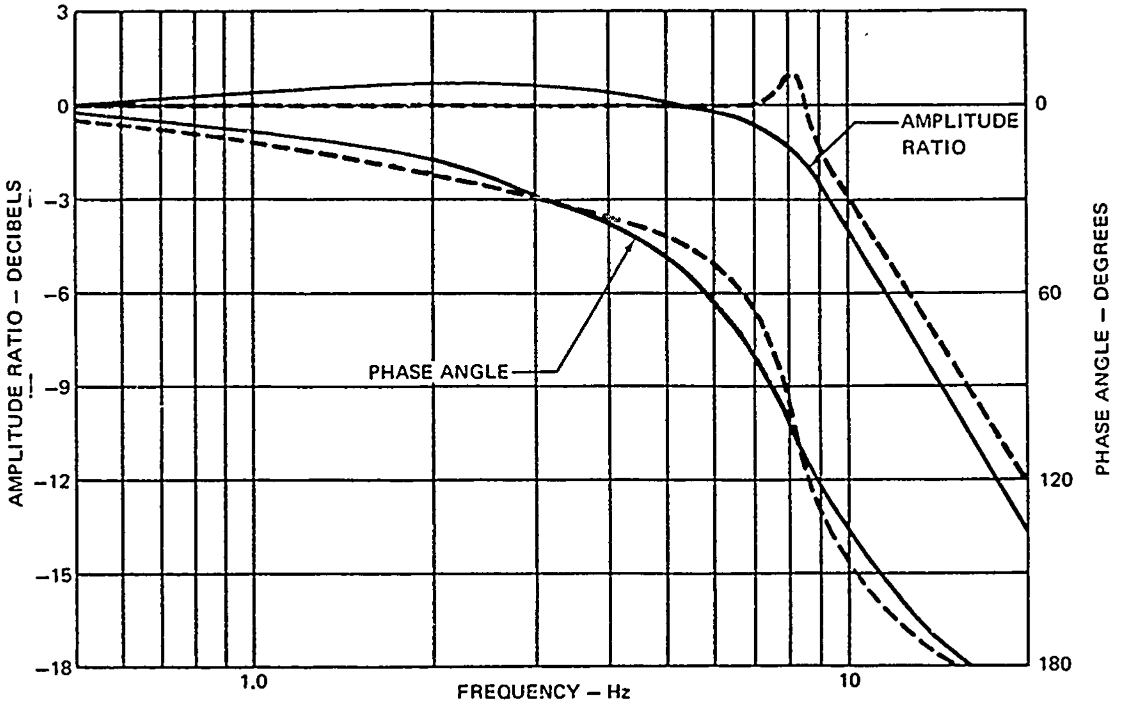

FIGURE 19. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: CHANNEL 1 VOTER INPUT DISENGAGED

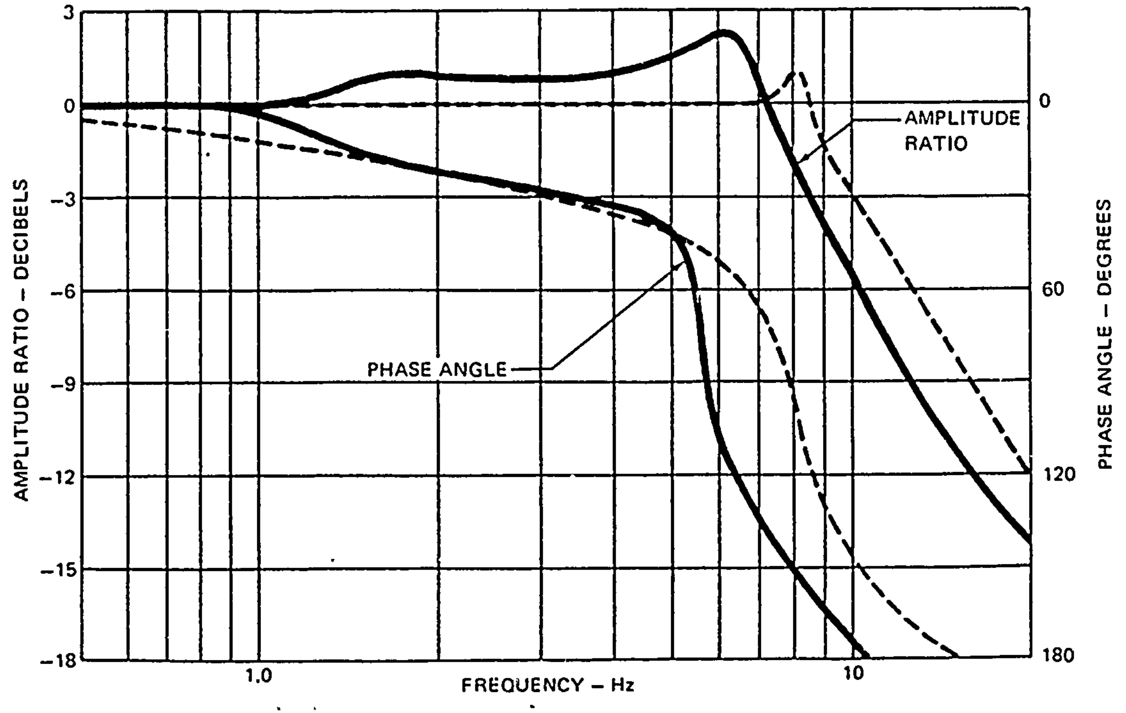

FIGURE 20. FREQUENCY RESPONSE – NORMAL CONDITIONS EXCEPT: WITH LOAD AND CHANNELS 1 AND 3 MOD PISTONS HARD OVER IN OPPOSITE DIRECTIONS

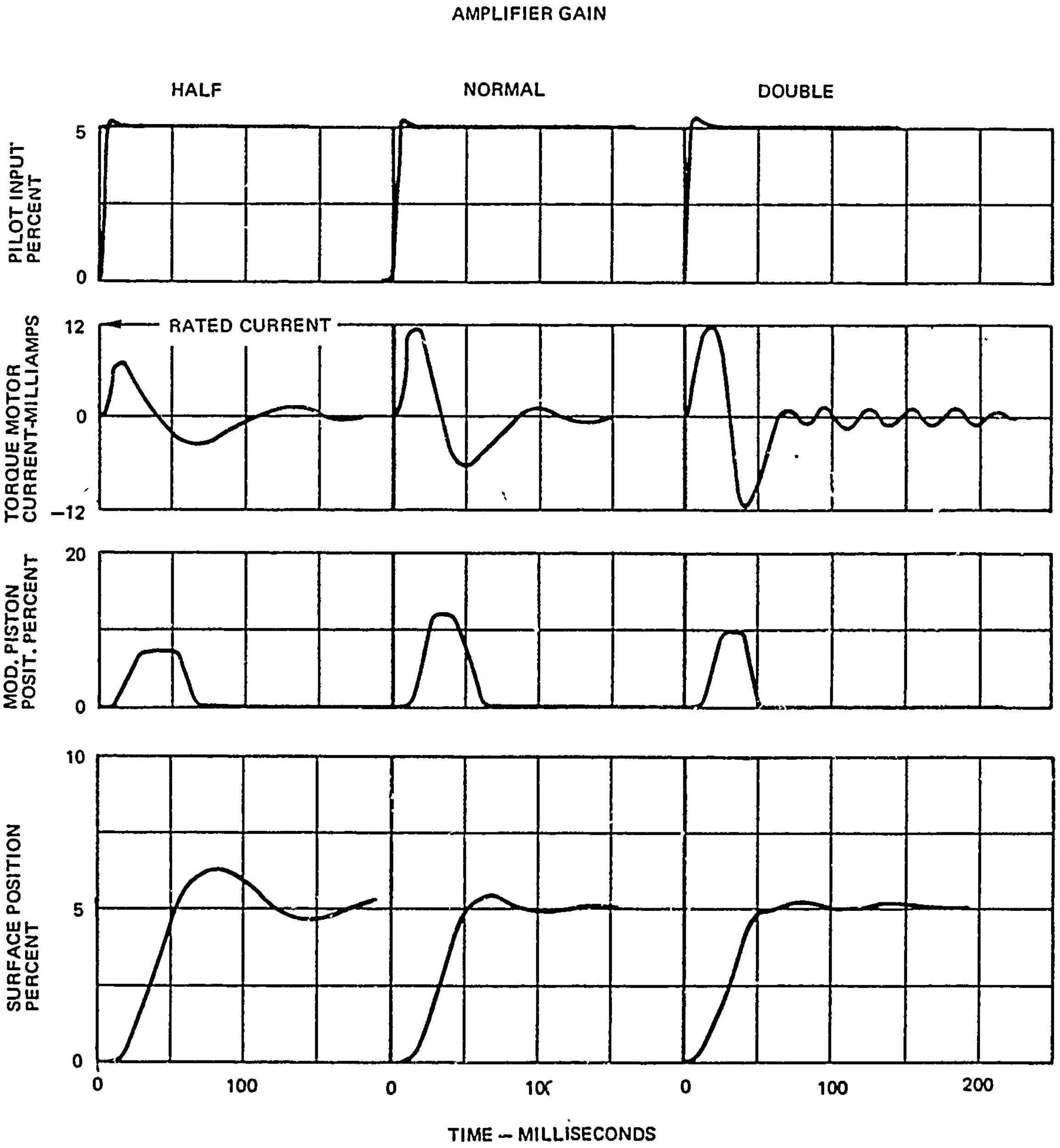

FIGURE 21. EFFECT OF AMPLIFIER GAIN ON TRANSIENT RESPONSE

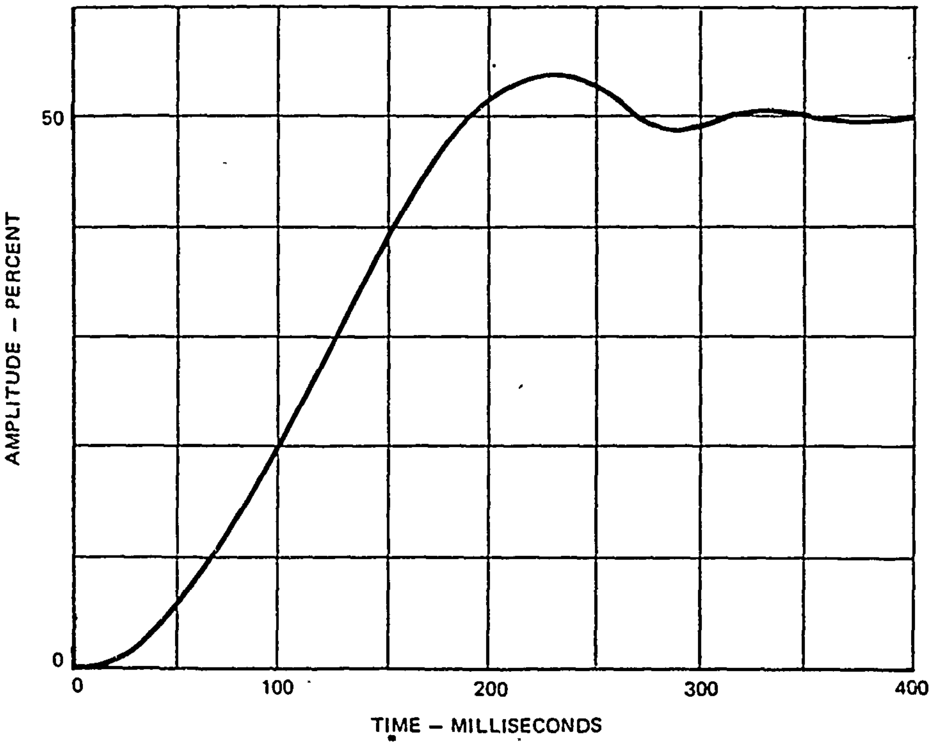

FIGURE 22. TRANSIENT RESPONSE TO LARGE STEP INPUT