FLY-BY-WIRE FLIGHT CONTROL SYSTEMS

By

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3 SEPTEMBER 1968

Prepared for

Joint Meeting of Flight Mechanics and
Guidance and Control Panels of AGARD

Oslo, Norway

39

AD 679 158

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Introduction

The purpose of ~~this~~ these paper is to provide the reader with an introduction to fly-by-wire and an outline of state-of-the-art fly-by-wire techniques. An outline of the philosophy of fly-by-wire flight control systems is given, the evolution of fly-by-wire is discussed, the advantages of fly-by-wire over mechanical systems are listed, current fly-by-wire techniques are outlined, and a brief review of the Air force Flight Dynamics Laboratory proposed in-house and contracted fly-by-wire development programs is given.

The Philosophy of Fly-by-Wire

Before discussing fly-by-wire, it is important to understand what is meant by the term "fly-by-wire". Two other terms, "electrical primary flight control system" and "pseudo fly-by-wire", are often used in discussions of fly-by-wire and therefore also require definition. The following definitions of these three terms apply throughout this paper and have been generally accepted by the Air Force Flight Dynamics Laboratory.

Electrical Primary Flight Control System (EPFCS) - A flight control system mechanization wherein the pilot's control commands are transmitted to the moment or force producer only via electrical wires.

Fly-by-Wire - A fly-by-wire flight control system is an electrical primary flight control system employing feedback such that vehicle motion is the controlled parameter.

Pseudo Fly-by-Wire - A fly-by-wire flight control system with a normally disengaged mechanical backup.

Fly-by-wire, that is, the complete replacement of the mechanical linkages between the pilot's stick and the control surface actuators by electrical signal wires, offers a convenient and logical solution to many of the control system problems associated with modern high performance aircraft and aerospace vehicles. However, there exists a strong reluctance on the part of both pilots and flight control system designers to remove all flight control cables and mechanical linkages and rely solely on electrical signals and electronic devices. Nor is this reluctance unreasonable. Since the Wright Brothers first flew at Kittyhawk in 1903, there has been some form of direct mechanical linkage between the pilot and the control surfaces or control surface actuators. The successful use of such systems has resulted in the growth of a sense of security toward mechanical control linkages which now tends to inhibit fly-by-wire development. "Security is a mechanical flight control system" quips Snoopy as he pursues the Red Barron (Figure 1). Yet in today's high performance aircraft, security is

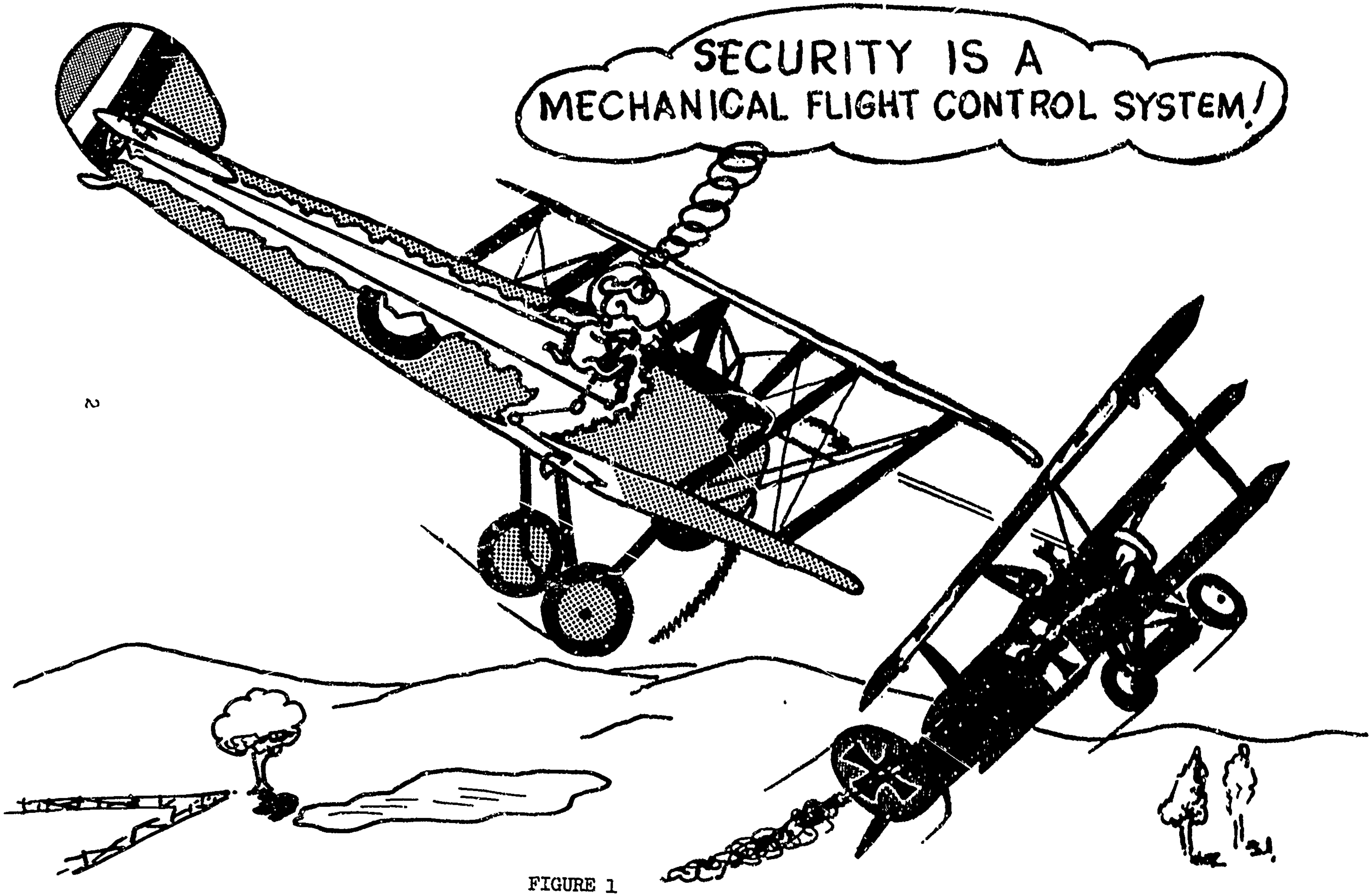


FIGURE 1

definitely not a mechanical control system. Instead, security is having a reliable Stability Augmentation System (SAS). For without SAS many high performance aircraft are only marginally stable and must, therefore, rely on electronic devices (black boxes) for the successful completion of a mission. In such cases, an effort has been made to obtain some of the advantages of fly-by-wire without losing the "security" of a mechanical system with the result that many of the disadvantages of the mechanical system are retained. The state-of-the-art in electronic circuits and redundancy techniques has now antiquated this approach. It is now possible to talk realistically about building a pure fly-by-wire flight control system that is more reliable than its mechanical counterpart. Until it is actually done, however, and successfully demonstrated in flight tests, the Missourian in many of us will prevail and the security stigma associated with mechanical control systems will predominate. Our fly-by-wire effort is orientated towards fulfilling this need.

The Evolution of Fly-by-Wire

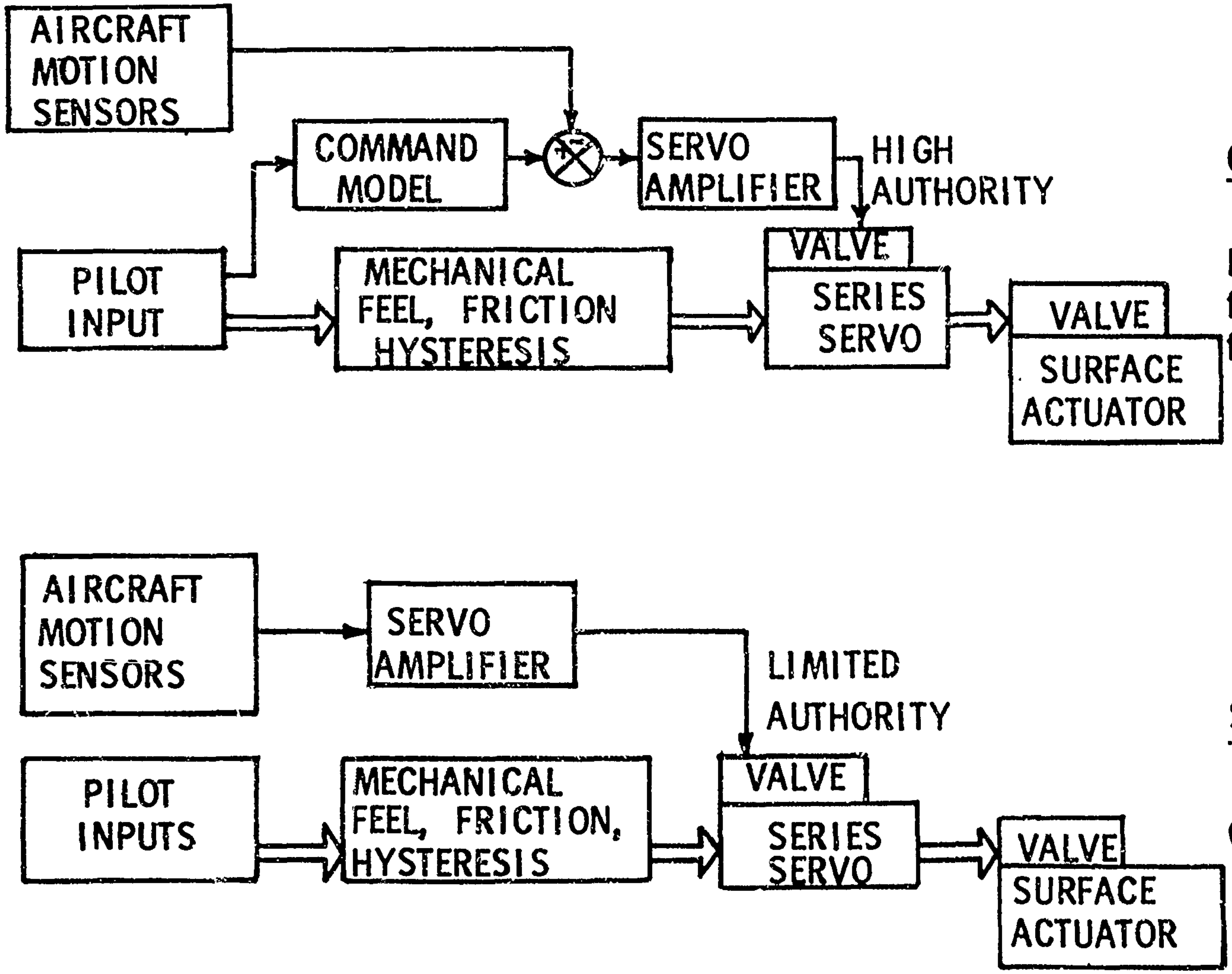
The concept of fly-by-wire is not something which sprung up over night, but rather it evolved slowly through the years as aircraft flight control system requirements changed. With progressive increases in aircraft size and speed, power-boosted control quickly became a requirement in order to enable the pilot to utilize the full maneuver capability of the aircraft. Hydraulic boost, where a hydraulic actuator is connected in parallel to add to the pilot's force on the control cables, is still used on many aircraft; for example, the B-47, T-33, 707 rudder, and 727 elevators and ailerons. Shortly after World War II, fully powered controls came into being. Here the control cables from the pilot's stick are attached directly to the spool of the servo valve on the actuator and are in no way physically connected to the control surface Feel is introduced into the system artificially with springs, dash pots, bob weights, and in some cases "q" bellows. This artificial feel, while not required in moving the control surfaces, is needed to give the pilot the proper handling qualities characteristics for control of the aircraft. Hence, although the pilot has no direct physical connection with the control surfaces, the artificial feel system gives him the impression that he has. Examples of aircraft using fully powered controls are the F-86, F-4C, F-104, F-105, and 727 rudder. One of the primary reasons for using fully powered control is that in the transonic region the forces on the surfaces vary greatly and are highly nonlinear. The resulting stick forces with direct mechanical connection to the control surfaces were unacceptable from a handling qualities point of view. Fully powered controls are inherently irreversible and thus unaffected by nonlinearities in the transonic region, allowing the artificial feel system to be designed to give smooth transition from subsonic to supersonic flight.

As aircraft continued to increase in size and performance, it became necessary to add stability augmentation to assist the pilot in his control task. Stability augmentation systems (SAS), having very limited authority, were added in series with the normal flight control system. For some aircraft in certain flight regimes, however, the proper functioning of the SAS was required for the very survival of the aircraft. The success of SAS led to the introduction of CAS, Control Augmentation System. A control augmentation system has an electrical system operating in parallel with the mechanical control system. The electrical system predominates by virtue of its high gain and servo authority and performs essentially as a fly-by-wire system. The step from CAS to pseudo fly-by-wire is a small one and involves declutching the mechanical system when it is not in use. To get a fly-by-wire system from a pseudo fly-by-wire system, one needs only to remove the mechanical flight control system entirely. Fly-by-wire flight control systems are currently used in some space vehicles. Figure 2 illustrates the SAS to CAS to FBW evolution.

Need for and Advantages of Fly-by-Wire

The flight control systems of yesteryear, which consisted of relatively simple direct mechanical linkages, cables, and feel springs, can no longer meet the demands of advanced aircraft control system requirements. The flight control designer has been forced to replace the simple manual control system with complex nonlinear linkages, mixing assemblies, power actuation devices, and active artificial feel systems containing literally hundreds of different parts and interconnections. In his struggle to meet rigid performance and environmental requirements (such as immunity to aircraft structural changes due to flexing and thermal expansion) the designer has been confined by the requirements for low weight and high reliability. Hence, a compromise is forced and the full potential of many aircraft is never realized because of the resulting control system limitations. The degree of complexity to which flight control designers have had to go in their effort to solve these problems is best illustrated by an examination of Figure 3 which depicts a portion of the flight control system of a typical high performance tactical fighter aircraft. You will note that the system is made up of a great number of relatively heavy push rods, bell cranks, and other linkages with a total of one hundred and fourteen bearing points. Each bearing point represents a source of friction and a possible failure point. Nor is the complexity of this example flight control system illustrated in Figure 3 unique. The B-70 flight control system is even more complex but would require such a large foldout to display that one might say it is beyond the scope of this paper. Helicopter flight control systems are also enormously complex and their problems were multiplied several fold with the introduction of V/STOL aircraft. Figure 4 illustrates what a simple nonredundant fly-by-wire system might look like. This fly-by-wire system would do the same task as that complex mechanical system shown in Figure 3 and do it better. We would not suggest,

COMPARISON OF STABILITY & CONTROL AUGMENTATION



CONTROL AUGMENTATION

Remove mechanical link from Pilot to Series Servo for "Fly-by-Wire"

STABILITY AUGMENTATION

Often called "Damper"

FIGURE 2

PITCH / ROLL MECHANICAL CONTROL SYSTEM

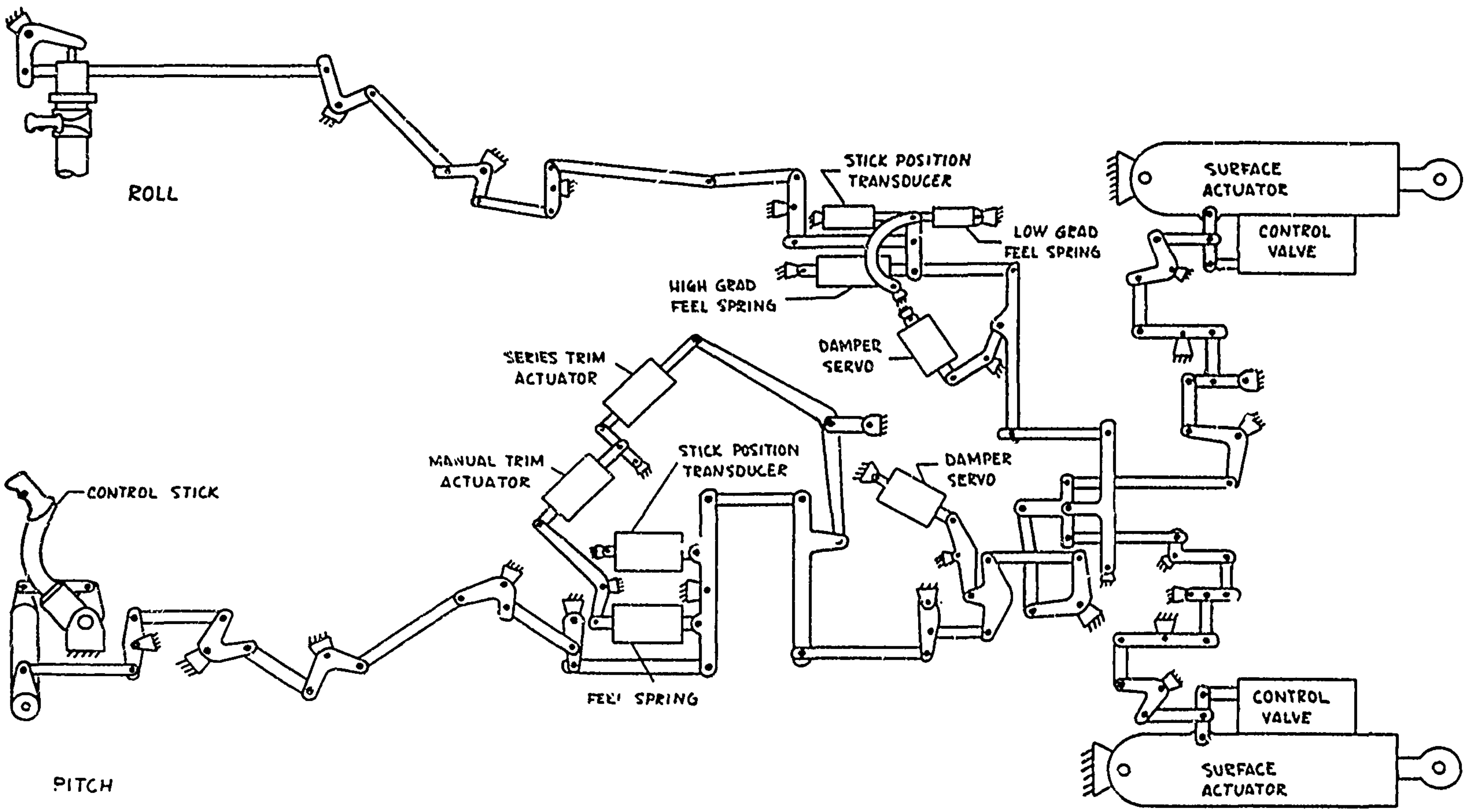


FIGURE 3

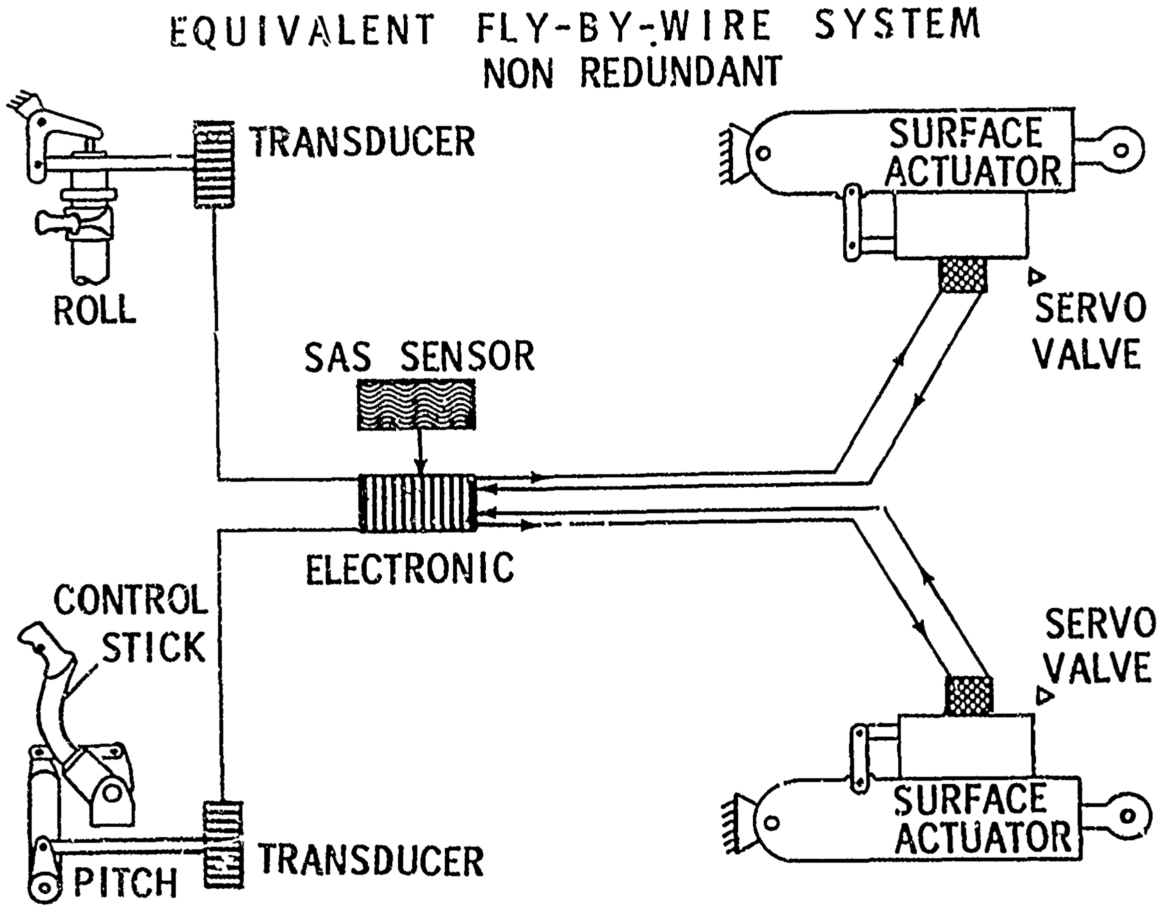

EQUIVALENT FLY-BY-WIRE SYSTEM
NON REDUNDANT
TRANSDUCER
ROLL
SURFACE ACTUATOR
SERVO VALVE
SAS SENSOR
ELECTRONIC
CONTROL STICK
SERVO VALVE
SURFACE ACTUATOR
PITCH
TRANSDUCER

FIGURE 4

however, that a simple nonredundant fly-by-wire system should ever be used in such an aircraft since its reliability would not be high enough for the mission requirement. A two-fail/operate or quadruply redundant fly-by-wire system, as shown in Figure 5, could meet all the requirements of a typical high performance aircraft including reliability. This additional redundancy can be added to the simple fly-by-wire system with little complexity or weight penalty and with a significant increase in reliability. Figure 6 illustrates, on a hypothetical tactical fighter aircraft, the relative simplicity of such a system especially when used with integrated servo actuator packages.

Many of the advantages of a fly-by-wire flight control system over the conventional mechanical flight control system are self-evident. Some, however, tend to become obscured by misinformation, skepticism, inertia, prejudice, or just plain ignorance. Below are listed some of the advantages of fly-by-wire with supporting facts and figures where available and applicable.

a. Design and Installation Savings - The design and installation manhour savings that can be realized by using fly-by-wire are fairly self-evident. Cable tension, routing, and maintenance accessibility are only a few of the many problems which are virtually eliminated by fly-by-wire design. North American Rockwell Corporation estimated that, based on large production quantities, approximately 5000 manhours per aircraft could be saved on the design and installation time of the flight control system for large, high performance, strategic bomber type aircraft.

b. Weight Savings - The weight saving that can be realized by using fly-by-wire is very significant when considered as a percentage of the flight control system weight. For example, Sperry Pheonix have estimated that as much as a 58% reduction in the flight control system weight, or approximately 277 lbs could be realized by using fly-by-wire on tactical fighter aircraft. General Dynamics Corporation estimated that an 84% reduction (535 lbs) in control system weight could be realized by using fly-by-wire on large, high performance, strategic bomber type aircraft. Lockheed Aircraft Corporation have estimated a savings of as much as 700 lbs by using fly-by-wire on large transport aircraft. A very significant savings in weight can also be achieved by using fly-by-wire on helicopters. Vertol estimates a savings of up to 86% (718 lbs) could be realized by using fly-by-wire on helicopters similar to those in current use.

c. Volume Savings - The volume savings realized by using fly-by-wire is particularly significant on high performance aircraft. Sperry Phoenix estimated that a reduction in volume of 1469 cubic inches could be effected by using fly-by-wire on tactical fighter aircraft. For strategic bomber type vehicles the volume reduction is even more

EQUIVALENT FLY-BY-WIRE SYSTEM
QUADRUPLY REDUNDANT

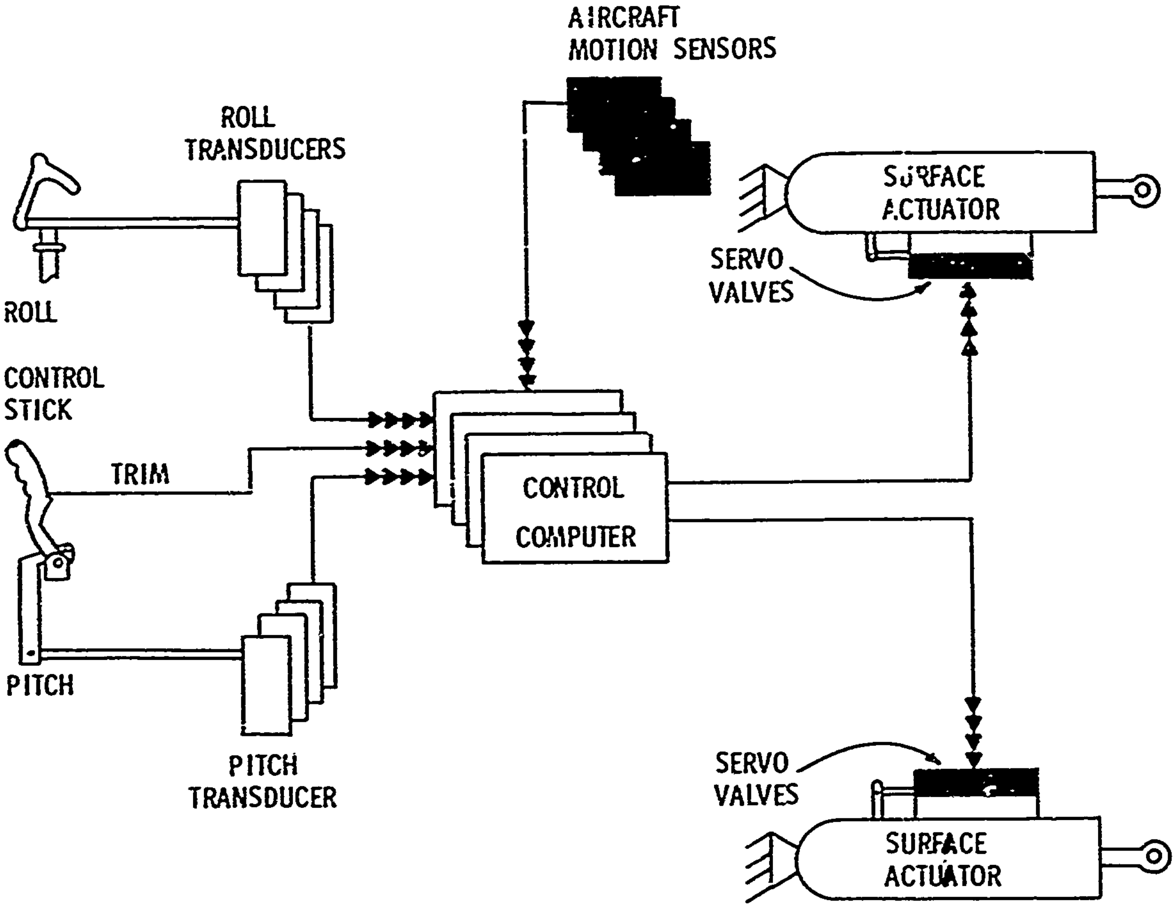


FIGURE 5

TWO FAIL OPERATE FLY-BY-WIRE FLIGHT CONTROL SYSTEM

NOTES:

1. Three independent electrical power supplies required (not shown)
2. Cable bundles shown may include power cables (3 to each actuator)
3. Actuator packages may he armoured and shaped for maximum survivability
4. Sensor package may be readily armoured since it is located in the cockpit area

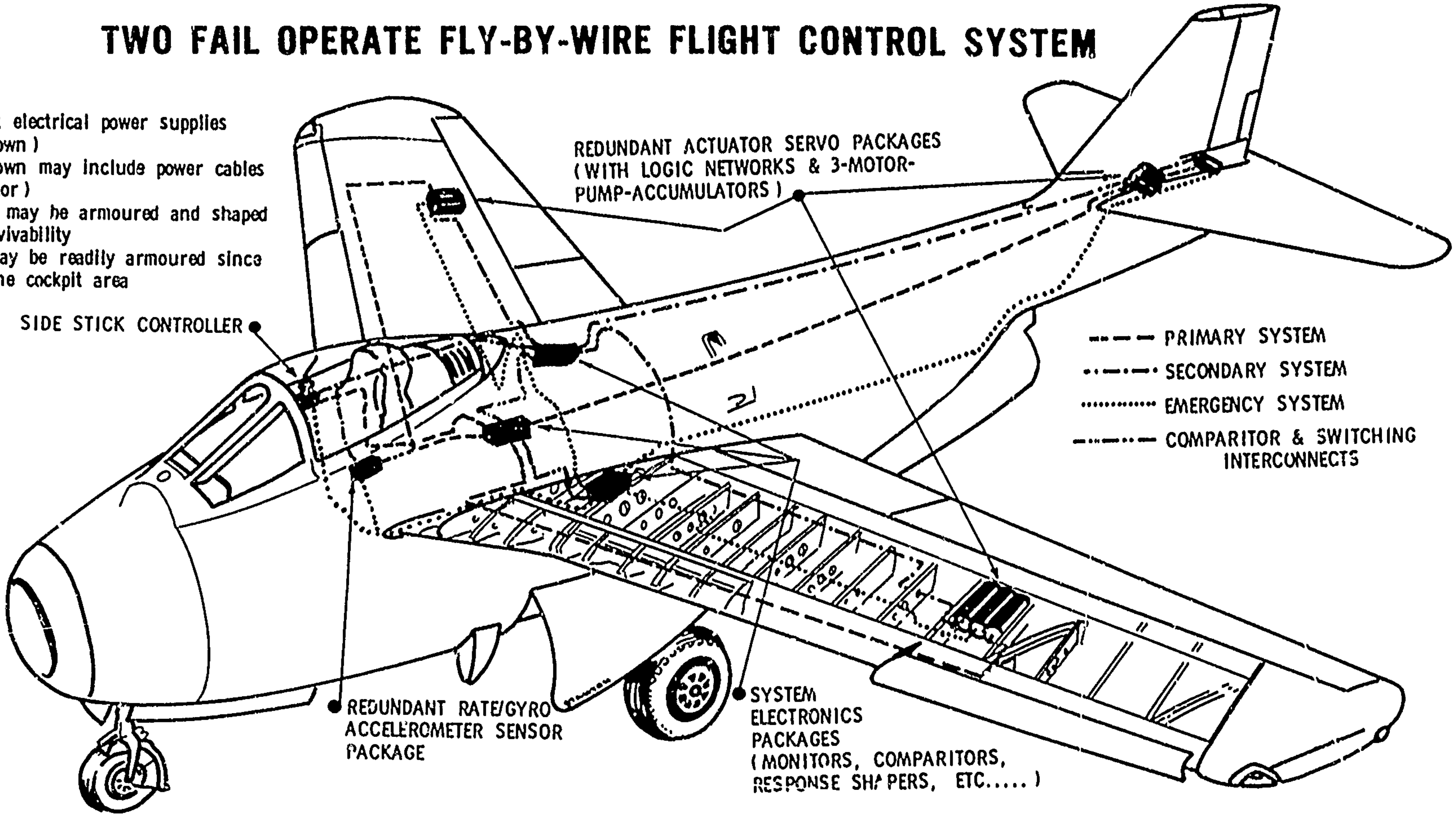


FIGURE 6

impressive. General Dynamics estimated that by eliminating control cable routing tunnels and motion clearance areas for the mechanical linkages a reduction of 156 cu ft could be saved using fly-by-wire.

d. Increase in Flight Control System Reliability - Using a two-fail/operate approach, a net increase in system reliability can be realized. It should be noted that besides increasing the reliability number that can be applied to the flight control system, this degree of redundancy also takes care of unpredictable failures due to such things as maintenance oversights, an act of nature, or an inflight crew or passenger action, all of which are normally catastrophic failures with the conventional mechanical system. The probability of flight control system failure for a one-hour flight as derived from the maintenance records of the Civil Aeronautics Board and the Federal Aviation Agency for the period of 1952 to 1959 is 2.3×10^{-7}. (Ref 3) This value establishes the nominal reliability criteria for fly-by-wire. Using a two-fail/operate or quadruple redundancy approach where two of four channels must operate for system success, this criterion can be met with a single channel failure rate per hour of 2.7×10^{-3}. This is well within the current state-of-the-art.

e. Reduction in Maintenance Manhours - Contrary to popular belief, a fly-by-wire system could actually result in a reduction in control system maintenance manhours. Modular packaging would permit the rapid repair of failed units, and the expensive and time consuming rerigging which must now be periodically done, would be eliminated. Built in test equipment (BITE) would quickly detect and isolate failed components and these could then be replaced by new ones. An increase in the frequency of failure occurrence would be expected, but the ease of failure isolation and repair would more than offset this increase. North American Rockwell estimated that for a high performance strategic bomber type aircraft, a reduction in maintenance manhours per flight hour of about 10% could be attained by using fly-by-wire with a resulting 3.5% decrease in aircraft down time. Vertol estimated that for complex control systems such as are used in helicopters and other V/STOL aircraft, a reduction in control system maintenance manhours of as much as 80% or more could be realized by using fly-by-wire.

f. Improved Aircraft Handling Qualities - Mechanical control system nonlinearities such as stiction, friction, and hysteresis are eliminated by using fly-by-wire. The aircraft response versus feel (stick force) can be readily adjusted to meet pilot desires at all flight conditions. A recently completed study (Reference 9) which applied linear optimal control theory to the problem of control blending (phasing) and attitude stabilization and control for VTOL aircraft, and which used the Bell X-22A ducted-propeller VTOL aircraft as the application vehicle emphasizes the improvement in handling qualities with fly-by-wire. During this study, Bell Aerosystems test pilots on the X-22A project evaluated, using Cooper rating, X-22A transition controller designs on a six degree of freedom flight simulator. Comparative flight tests were done usingg the present X-22A control system, an optimal controller tied into the existing mechanical blender, and finally, an optimal controller using fly-by-wire. From the results of these evaluations, as shown in Table I, it is evident that a very significant improvement in handling qualities can be gained by using fly-by-wire on VTOL aircraft.

TABLE I

Pilot Cooper Ratings for the Several

X-22A Transition Controller Configurations

Control System Configuration	Pitch		Roll		Yaw	
	Hover	Transition	Hover	Transition	Hover	Transition
Optimal Controller With Fly-by-Wire	2.0	2.25	2.0	2.5	2.5	2.5
Optimal Controller With Existing Mechanical Blender	2.75	3.0	3.0	3.0	3.25	3.25
Present Control System	3.0	3.5	3.5	3.5	3.5	3.75

A convenient method for mechanizing the flight control system feel/response is the C* approach as proposed by Boeing. This approach, which has gained some popularity, uses a linear blend of normal acceleration, pitch rate, and pitch acceleration. C* is defined as:

$$C^* = k_1 n_z + k_2 \dot{\theta} + k_3 \ddot{\theta}$$

where

n_z = normal acceleration at the c.g., positive up

$\dot{\theta}$ = pitch rate

$\ddot{\theta}$ = pitch acceleration

If C* is defined in g's, we find that the units of k_2 are equivalent to a velocity divided by g and k_3 is equivalent to the distance between the linear accelerometer and the c.g. of the aircraft divided by g. By setting k_1 equal to 1, the equation may now be written:

$$C^* = n_z + \frac{U_{co}}{g}\dot{\theta} + \frac{L}{g}\ddot{\theta}$$

where

U_{co} = the cross over velocity (approximately equal to 400 ft/sec)

L = the distance between the linear accelerometer and the c.g. of the aircraft

The crossover velocity represents the point where the contribution of pitch rate and normal acceleration to the C* equation are equal. (This does not necessarily mean that this is the velocity at which the pilot attaches equal importance to them.) C* is a convenient approach for the mechanization of a feel system because of the ease with which $\dot{\theta}$ (pitch rate) and $\ddot{\theta}$ and n_z (pitch and normal accelerations respectively) can be measured. These variables are often already being sensed in the stability augmentation system. Figure 7 shows a typical fly-by-wire flight control system with C* feedback. Figure 8 illustrates one method of specifying a handling qualities criterion in terms of the C* mechanization. These boundaries were obtained by reducing the results of the handling qualities studies conducted by Cornell on the F-94 (Reference 2).

g. Immunity to Aircraft Structural Changes Due to Flexing, Bending, Thermal Expansion, Etc. - Mechanical control systems are very sensitive to aircraft structural changes and great pains must be taken by the designer to try and minimize their effects. With fly-by-wire their effects are inherently eliminated. The fact that an SST will increase in length by approximately 7 to 12 inches due to aerodynamic heating is of little concern to the designer of a fly-by-wire control system. It is even possible to incorporate a form of structural mode stabilization into a fly-by-wire system to give the airframe an effective rigidity and thus increase its fatigue life. This concept is presently being investigated by the Air Force Flight Dynamics Laboratory on a B-52 aircraft at Boeing Wichita in a program called LAMS (Load Alleviation and Mode Stabilization). The initial goal of this program was to improve aircraft structural fatigue life by 100%. The pre-flight analysis effort on the test aircraft which included a 35 degree of freedom computer simulation indicated that the sought improvement in structural fatigue life could generally be met and in some cases greatly exceeded. A preliminary analysis of the actual flight test data supports these conclusions. The following table shows the improvement obtained at certain stress locations (Wing Stations, Body Stations, Stabilizer Butt Line, Fin Station). Along with these benefits, a 20% improvement in rms acceleration at the pilot station was achieved.

SIMPLIFIED BLOCK DIAGRAM OF FLY-BY-WIRE CONTROL SYSTEM-PITCH AXIS

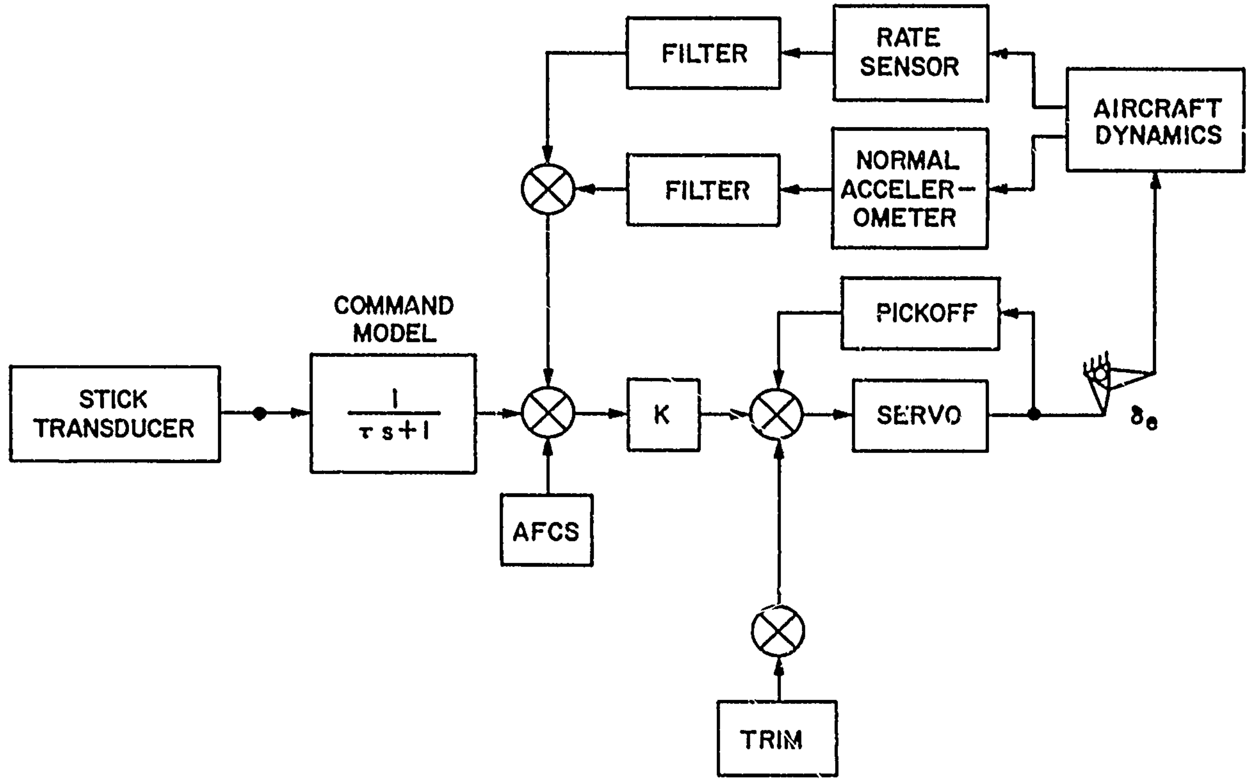
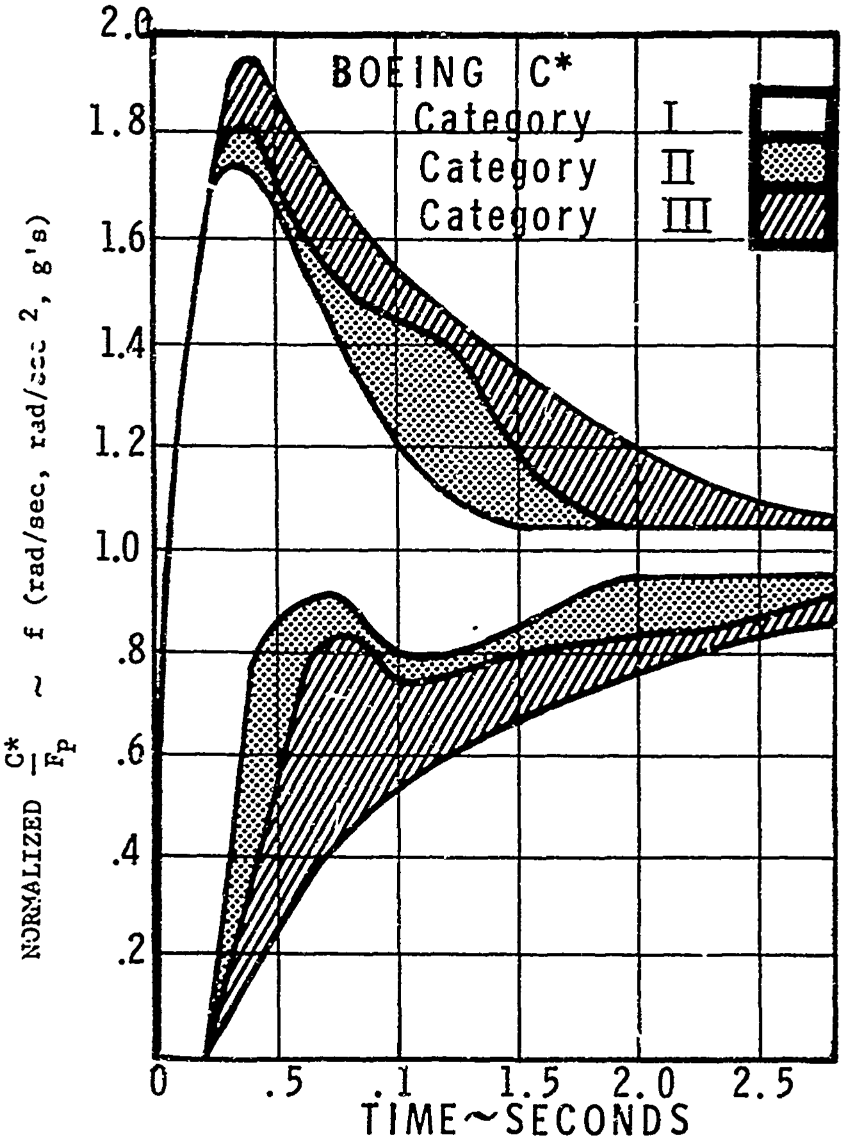


FIGURE 7



VARIOUS $\frac{C^*}{F_p}$ STEP RESPONSE ENVELOPES

FIGURE 8

TABLE II

Fatigue Damage Per Flight Hour

Stress Location	WS 516	WS 899	BS 805	BS 1028	SBL 32	FS 135
Basic A/C	$2.3\text{x}10^{-3}$	$2.2\text{x}10^{-3}$	$.58\text{x}10^{-3}$	$.78\text{x}10^{-3}$	$.059\text{x}10^{-3}$	$1.0\text{x}10^{-3}$
LAMS Control Sys	$.4\text{x}10^{-3}$	$1.2\text{x}10^{-3}$	$.09\text{x}10^{-3}$	$.2\text{x}10^{-3}$	$.027\text{x}10^{-3}$	$.17\text{x}10^{-3}$
Factor of Improvement	5.75	1.83	6.45	3.9	2.18	5.9

h. Flexibility of Cockpit Layout - Fly-by-wire permits the use of side stick controllers and other forms of miniature controllers. Thus, the pilot's view of the instrument panel need no longer be obstructed by a large, center-mounted control stick. A variety of side stick and miniature controllers have been investigated and flown, and at present it would appear that the most acceptable type of side stick controller would be a displacement (rather than rigid) stick with a grip which is smaller than that currently being used. Another big advantage which comes from using a side stick controller with suitable arm rests or supports is the elimination of the effect of g's on the pilot's input to the stick.

i. Ease of Incorporation of Automatic Flight and Landing Systems - Fly-by-wire eliminates the requirement for series and parallel servo actuators and complex blending and mixing linkages for Automatic Flight Control Systems (AFCS) and Automatic Landing Systems (ALS) since all inputs are electrical and summing is done electronically forward of the servo power actuator. Furthermore, fly-by-wire has its own built-in stability augmentation system.

j. More Flexible to Design or Performance Changes - Fly-by-wire is affected very little by configuration or system performance changes which might be introduced during the production phase. This is true because of the inherent flexibility of fly-by-wire design, and the fact that sensed vehicle motion is the controlled variable rather than control surface position.

k. Decrease in Airframe Static Stability Requirements - Once fly-by-wire has been accepted as a point design and the flight safety of the aircraft relies on its continued operation, the static stability of the basic airframe may be of little importance. The airframe designers and aerodynamicists are thus allowed a completely new freedom of design which up to this point has always been limited by the requirement that the basic airframe should be stable without any control inputs. The doors which this new freedom open are many and may well lead to the design of aircraft which are more maneuverable, lighter weight, have less drag, and perform the specific mission for which they are designed in a much more optimal manner than current design practices allow. The total impact this will have on future aircraft, and the advantages which can be gained thereby, go far beyond those available by simply replacing a mechanical flight control system with a fly-by-wire counterpart.

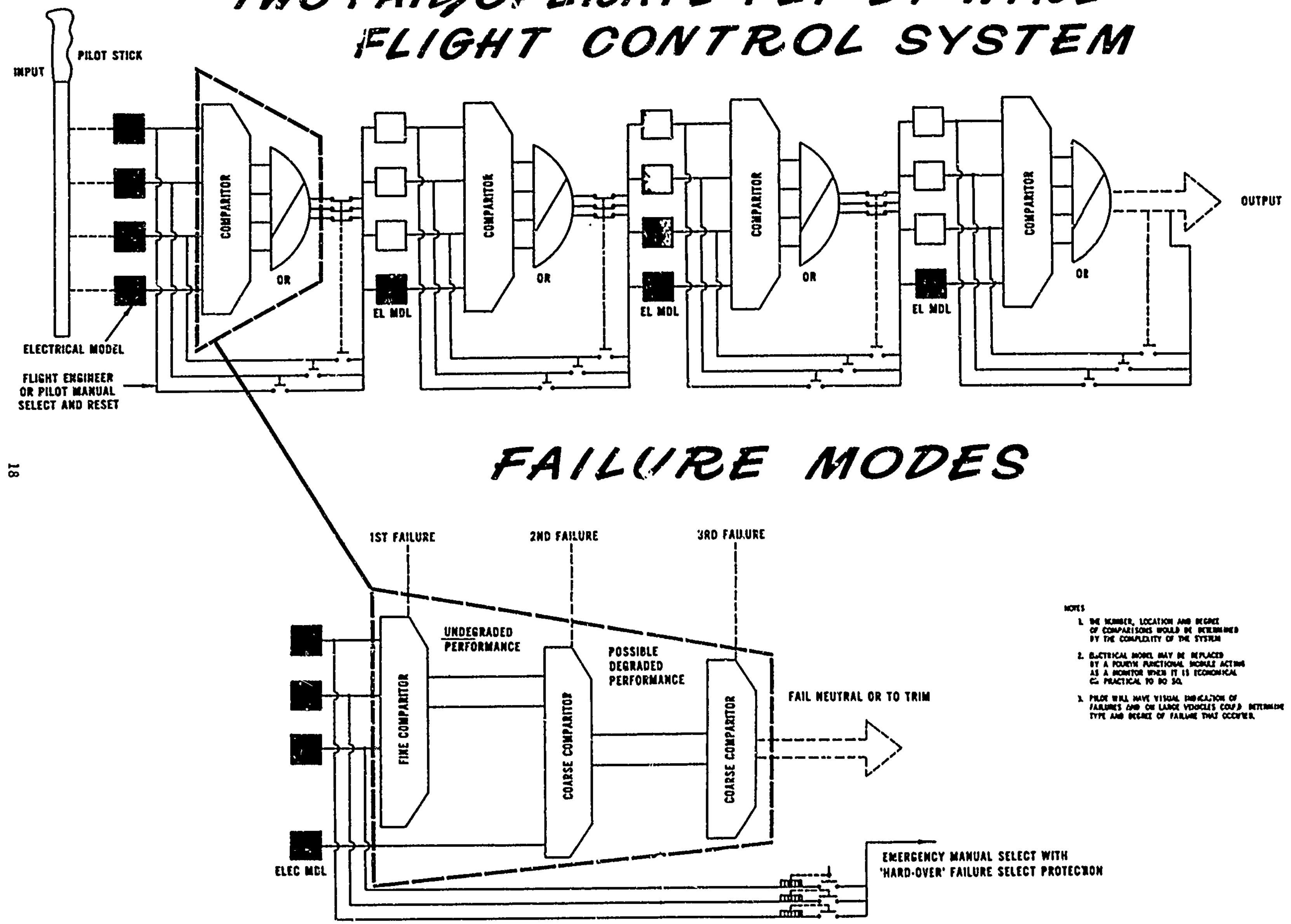
1. Decrease in Cost of Ownership - Each of the above factors contribute to an overall decrease in the total cost of ownership of aircraft with fly-by-wire flight control systems, a fact of major importance to both the Government and to commercial airlines.

Description of Fly-by-Wire Flight Control Systems

Degree of Redundancy

One of the first problems which faces the designer of a fly-by-wire flight control system, once he has decided to eliminate any form of mechanical backup, is the degree of redundancy to design into the system. Two factors must influence his decision: first, the reliability required, and second, the failure-mode philosophy, both of which are dependent on vehicle mission. Our studies to date have indicated, that for large advanced military or commercial aircraft, the most acceptable degree of redundancy would be one which would provide a two-fail/operate capability, thus allowing completion of mission after any single failure. This is sometimes referred to as quadruple redundancy and will accept two like failures in the system with little or no system performance degradation. On a third similar failure, the system goes to a neutral (soft) or pre-selected trim position. In this system, the pilot and/or flight engineer could have the option of bypassing each logic section and positively selecting each functional module throughout the control system. This would permit the pilot, after three like failures, to make full use of any system capabilities which might remain. A module which failed to produce acceptable performance for normal operation might thus be successfully used to get the aircraft home. This two-fail/operate philosophy is illustrated in Figure 9. Here three functional modules and an electrical model are used to give the quadruple redundancy. The number of comparators and their location in the system and the type of logic to be used (median select, majority vote, etc.) are optional. These and the degree of performance degradation allowable after a second failure would be determined at the time of system design. The advantage of using several sets of comparators and logic networks throughout the system as opposed to a single set at the output of each channel is obvious from this figure when it is noted that the hypothetical flight control system depicted here could withstand eight (8) distinct failures and still be fully operable provided no three failures were alike; i.e., one functional module of each set must be serviceable. The system, however, should not contain any "nodes" where all channels feed into a single comparator or black box, the failure of which would wipe out the entire control system. The comparators should also be redundant,

TWO-FAIL/OPERATE FLY-BY-WIRE FLIGHT CONTROL SYSTEM



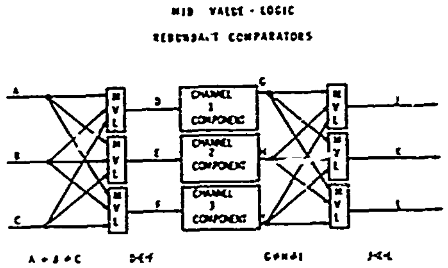
NOTES

1. THE NUMBER, LOCATION AND DEGREE OF COMPARISONS WOULD BE DETERMINED BY THE COMPLEXITY OF THE SYSTEM
2. ELECTRICAL MODEL MAY BE REPLACED BY A FOURTH FUNCTIONAL MODULE ACTING AS A MONITOR WHEN IT IS ECONOMICAL OR PRACTICAL TO DO SO.
3. PILOT WILL HAVE VISUAL INDICATION OF FAILURES AND ON LARGE VEHICLES COULD DETERMINE TYPE AND DEGREE OF FAILURE THAT OCCURRED.

FIGURE 9

a fact which Figure 9 does not depict. Further, if a comparator should fail, it should be detected and switched out like any other failure. This is not to say that redundant monitors are required to monitor the operation of the redundant comparators that monitor the operation of the redundant modules!! Careful design of the comparators should accomplish this end without resorting to the ridiculous. Consider, for example, the redundant comparators shown in Figure 10 which use Mid-Value-Logic (MVL) techniques. For simplicity, only three channels are shown.

FIGURE 10



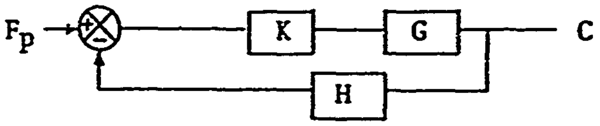
Where A ≠ B ≠ C; D = E = F; G ≠ H ≠ I; J = K = L

Redundant Electrical Power Supplies

The question which enters many pilots' minds when they first consider flying an aircraft with a fly-by-wire flight control system is, "What happens when I have a total electrical power failure?" The answer is intuitively obvious. Precautions must, therefore, be taken to ensure that such a catastrophe never occurs. The word never is too absolute; but what can and must be done is to redundacize the electrical power generators to such a degree that the chance of a complete electrical power failure occurring is no greater than the chance of an entire flight control system failure occurring for some other reason (or perhaps of the wings falling off). A two-fail/operate capability is required here, also, and since power supplies are inherently fail-passive, i.e., a hardover failure is impossible, this capability can be achieved with three independent power sources. Furthermore, an engine-out capability will be required to permit the pilot to control the aircraft while attempting a re-light or, in some cases, to perform a "dead-stick" landing. One of the power sources must, therefore, be an auxiliary power unit which will operate independently of the engines. A ram-air-turbine (rat) or even a battery may be sufficient to supply the power for this emergency operation. In the case of the Concorde supersonic transport, primary power is supplied to the electrical flight control channels by two 26 V 1800 cps static inverters supplied from the d.c. (battery) busbars. In this manner, voltage transients which might occur due to load switching and other causes are avoided. Modern aircraft have redundant electrical power supplies and experience with these systems indicates that it is well within the current state-of-the-art to provide redundant electrical power supplies that are sufficiently reliable for use with a fly-by-wire flight control system.

Theory of Closed Loop Flight Control Systems

It is far beyond the scope of this paper, not to mention the author, to attempt to give a comprehensive treatise on modern control theory. There are, however, certain fundamental relationships that must be understood before the full significance and importance of a high gain closed loop flight control system as is advocated for fly-by-wire can be appreciated. A simple closed loop system is shown here where F_p represents the control signal from the pilot's stick, K represents the gain or amplification factor in the control computer, G represents the aircraft transfer function, C represents the resulting aircraft motion, and H represents the gain of the rate gyros and accelerometers which detect the aircraft motion and feed a corresponding signal back to the input summer.



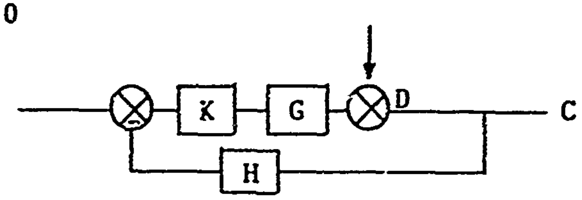
Then

$$\frac{C}{F_p} = \frac{KG}{1 + KGH}$$

Assume H = 1 (unity feedback)

Now raise the gain K so that KG is much greater than 1. Then C/F_p approaches 1; i.e., $C/F_p \longrightarrow 1$ which says that the aircraft responds exactly as commanded and thus is extremely easy to control.

Now apply a gust or disturbance D to the aircraft with no input; i.e., $F_p = 0$

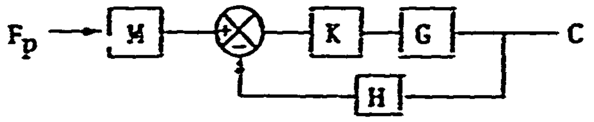


Then

$$\frac{C}{D} = \frac{1}{1 + KGH}$$

which for H = 1 and $KG \gg 1$, approaches 0; i.e., $C/D \longrightarrow 0$ which says that the aircraft has very little response to gust or disturbance inputs and, consequently, is very stable.

Experience has shown that pilots do not like the handling qualities of a flight control system which has a step response to a sudden input. Consequently, an electronic filter or model is introduced prior to the summer which gives the desired handling qualities characteristics. Normally, this model is in the form of a lag circuit.



Then as before for $H = 1$ and $KG \gg 1$.

$$\frac{C}{F_p} = \frac{MKG}{1 + KGH} \longrightarrow M$$

which says that the aircraft flies like the model and this, of course, is the desired goal and we now have what is referred to as a Model-Following Control System. The desirable gust response characteristics have not been altered since $C/D \longrightarrow 0$ as before. For those who may suspect that the above is some form of mathematical wizardry which in practice probably would not work, let me assure you that such systems do work as advertised. The control augmentation systems (see Figure 2) which are daily logging flight time on the F-111 and A-7A aircraft attest to this fact.

Typical Fly-by-Wire Implementation

A simplified block diagram for a single axis fly-by-wire control system was shown in Figure 7. A more complete representation of a quadruply redundant three-axis system is depicted in Figure 11. No effort has been made here to show the type or location of monitors and comparators nor has any attempt been made to outline the contents of each block in the diagram. These details are completely dependent upon the system application; and if the reader desires such information, it may be obtained from the referenced literature.

Sensors, Transducers and Electronics

One of the things which makes a two-fail/operate or quadruply redundant scheme feasible is the current state-of-the-art of sensors, transducers, and electronics. Small, reliable, lightweight, and relatively low cost sensors and transducers are available as off-the-shelf hardware. The penalty which must be paid for using quadruple redundancy is thus minimized. Sensors of the future currently under development at the Air Force Flight Dynamics Laboratory promise to reduce this penalty even further. An example of this is the DART sensor (Figure 12) which uses rotating mercury to sense rate of rotation and linear acceleration in two axes. A quadruply redundant sensor package measuring pitch rate and normal acceleration could be contained in a package 6" x 3" x 3" weighing less than three pounds. The electronics field has miniaturized even more so. Microelectronic circuits enable mixing, blending, voting, and, in general, response shaping to be done on a relatively small number of easily replaced cards. Metal oxide semiconductor (MOS) techniques decrease the size of these components by several orders of magnitude. Using these techniques it is now possible to redundacize electronics at a functional module level with a resulting decrease in size, weight, and cost and a net increase in system reliability.

QUADRUPLY REDUNDANT FLY-BY-WIRE FLIGHT CONTROL SYSTEM

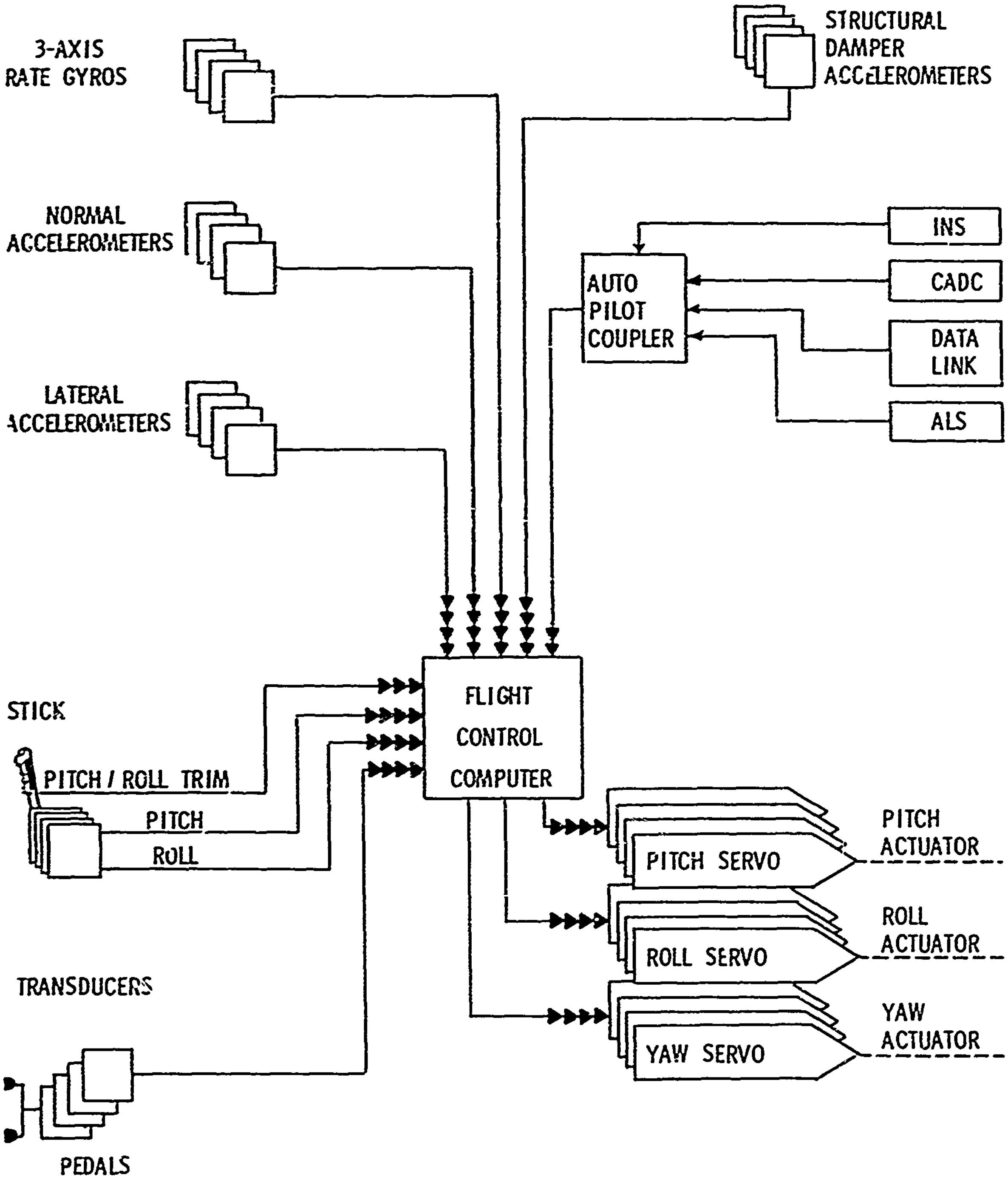


FIGURE 11

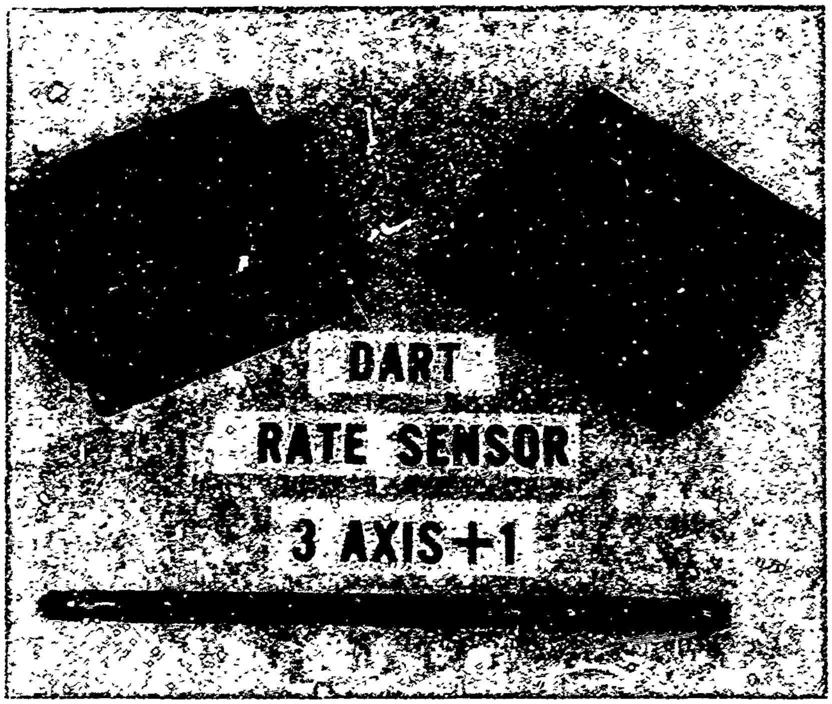


FIGURE 12 DART RATE SENSOR

Electrical Wiring and Connectors

The advent of fly-by-wire puts a completely new importance and priority on aircraft electrical wiring and connectors. The techniques presently being used in most aircraft would not be suitable for use on a system which will be a safety-of-flight item. The primary flight control wiring installation will require the same care and priority which is now given to control cables, fuel lines, and hydraulic lines. Isolation of the flight control wiring from the rest of the aircraft's wiring will be a must and special consideration will have to be given to dispersion, protective conduit and channeling to avoid maintenance damage, end-to-end hard wiring (i.e., no press-fit connections), protection against heat and fire damage, and cable jacket monitoring techniques which permit damage detection before an actual failure occurs. Where connectors are necessary, they must be designed to be "idiot proof" so that it is virtually impossible to force them together wrongly, even with the help of a large hammer. They must also be positively sealed to exclude moisture or other contaminants. A special effort should be made to eliminate electrical connectors wherever possible.

Redundant Fly-by-Wire Actuators

Until recently very little research work had been done in the area of redundant servo actuators at the two-fail/operate level. This discussion will be confined to hydraulic servo actuators since they appear to be most suitable for aircraft requirements of the immediate future. That is not to say that pneumatic, electrical, or other types of servo actuators will not be required or used on future aircraft. The redundant servo actuators currently under development fall conveniently into the following three categories: (a) electronic logic and switching; a two-fail/operate hydraulic servo actuator using electronic logic and switching technique has been designed by the General Electric Company (Johnson City) under the sponsorship of the Air Force Flight Dynamics Laboratory and is described in technical report AFFDL-TR-67-17 (see Figure 13), (b) fail passive with electronic logic; the Sperry Phoenix Company has designed a two-fail/operate, fail passive redundant servo actuator under their fly-by-wire contract with the Air Force Flight Dynamics Laboratory, and it is described in technical report AFFDL-TR-67-53 (see Figure 14), (c) hydraulic logic and switching; Hydraulic Research and Manufacturing Company has designed and built a single-fail/operate redundant actuator using hydraulic logic and switching which was installed and flight tested in an F-4C aircraft at Edwards Air Force Base this year (see Figure 15). A similar two-fail/operate redundant actuator has been designed and is presently being built by HRM for flight tests during Phase III of our in-house fly-by-wire program to be explained later in the paper. Each of these techniques has specific advantages and disadvantages in comparison with one another. The first, electronic logic and switching, can make full use of the size and weight advantages to be gained by using MOS techniques. The use of well proven electronic logic techniques and the ease of fault detection and correction through the use of modular packaging also makes this method attractive. It does, however, require transformation from one power media to another; i.e., electrical to hydraulic, in order first

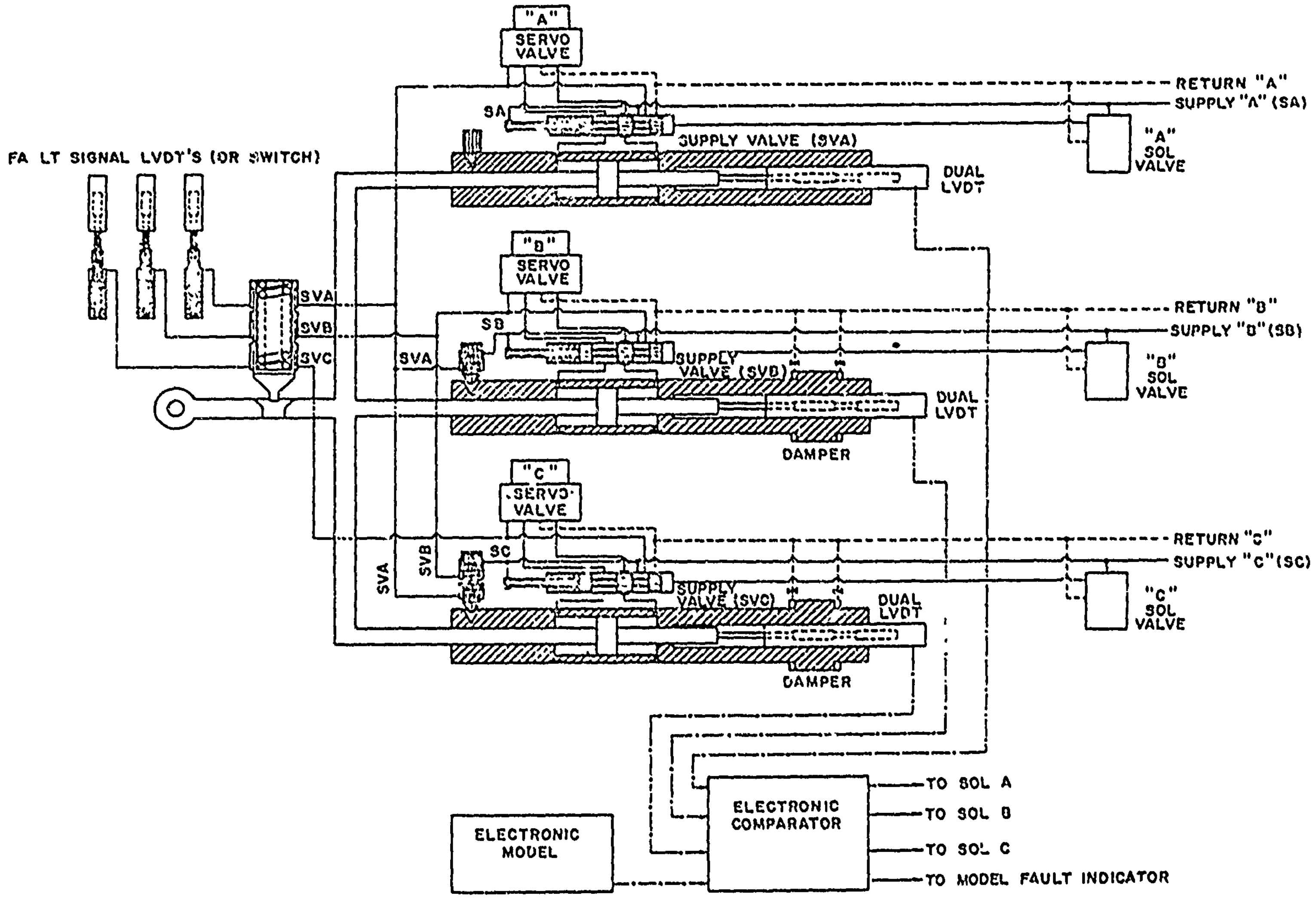


FIGURE 13 TRIPLEX ACTUATOR SCHEMATIC

ELECTRONIC LOGIC & SWITCHING

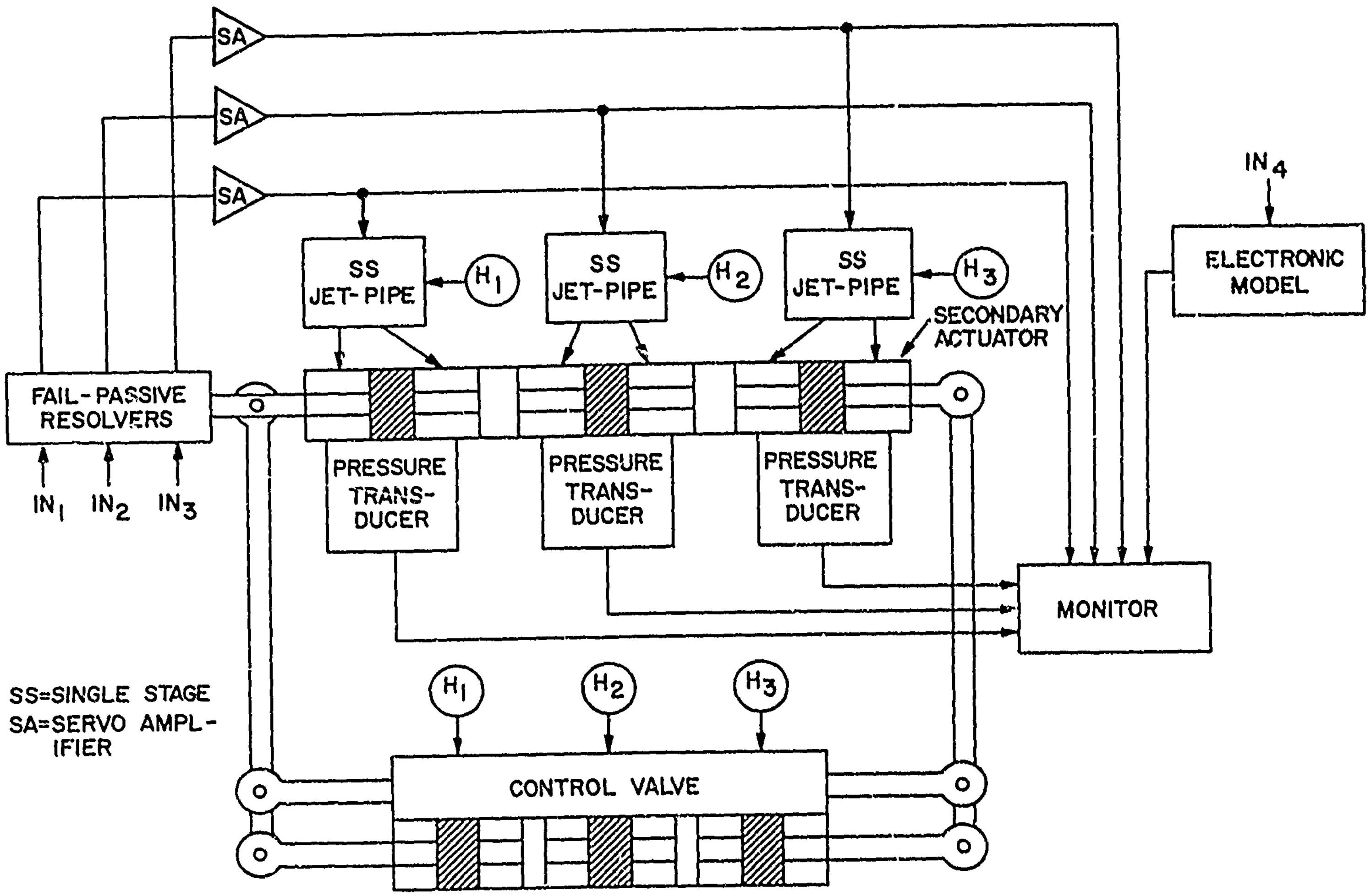
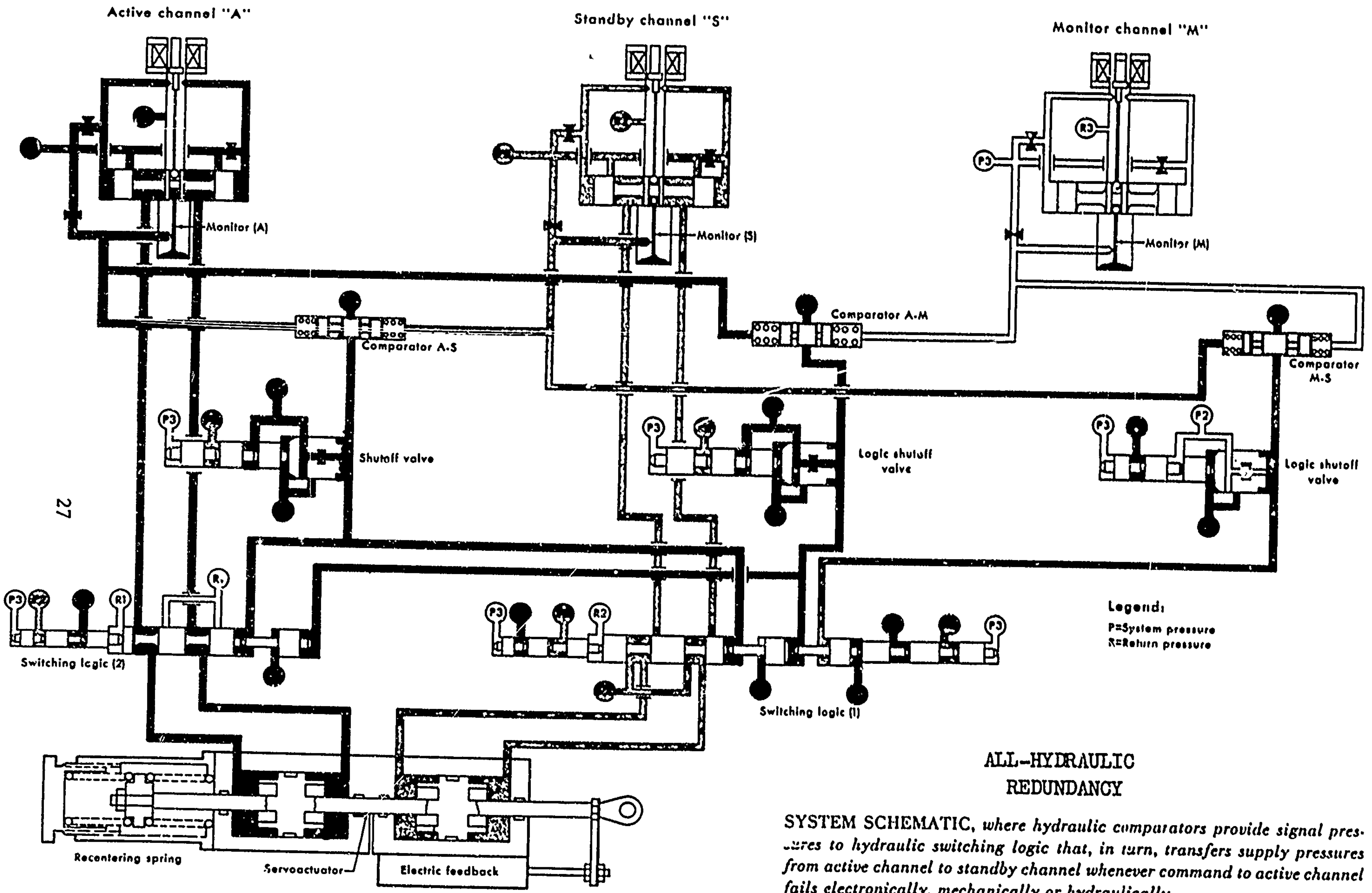


FIGURE 14 FAIL PASSIVE REDUNDANCY



ALL-HYDRAULIC
REDUNDANCY

SYSTEM SCHEMATIC, *where hydraulic comparators provide signal pressures to hydraulic switching logic that, in turn, transfers supply pressures from active channel to standby channel whenever command to active channel fails electronically, mechanically or hydraulically.*

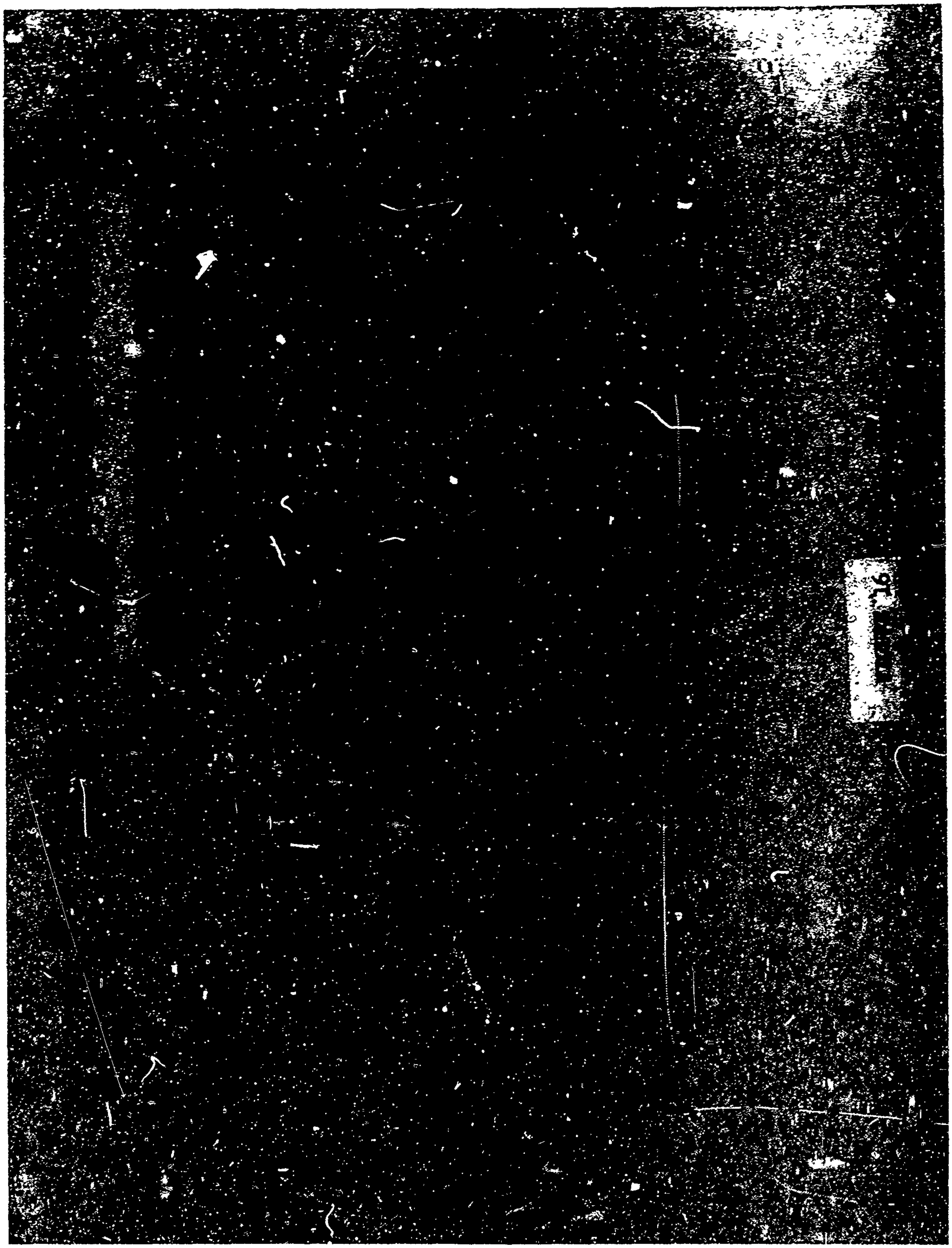
FIGURE 15

to detect the fault and second to correct it. The result is an increase in switching time and a decrease in reliability. A typical solenoid valve operates in 20 to 25 milliseconds. To keep the switching time down to a reasonable value (say 50 milliseconds), it would be necessary for the detection and electronic logic to take place in 25 milliseconds or less. Such a reaction time, although demanding, is within the current state-of-the-art. The second technique, fail passive with electronic logic, has the advantage of no switching transients since all servo valves are operating and when one or more fail passively, the remaining servo valves continue to drive the secondary actuator with negligible system performance degradation. This system has a further advantage of being able to supply two-fail/operate redundancy with three servo valves. The main disadvantage with this technique is that it is extremely difficult to design a 100% pure fail passive system. Consequently, it is necessary to include an electronic model as protection against a hardover failure even though the possibility of one occurring is remote. The third technique, hydraulic logic and switching, eliminates the power interface problem by performing all detection, logic, and switching functions in the hydraulic medium. The result is a decrease in switching time and an increase in reliability. Typical detection logic and switching times for such actuators are less than 10 milliseconds. These systems are sensitive to contamination and silting in the hydraulic fluid, but state-of-the-art filtering techniques can minimize this problem.

Integrated Hydraulic Servo Actuator Package Concept

The use of a hydraulic servo actuator package consisting of an electrically driven motor, hydraulic pump, accumulator, reservoir, servo valve and hydraulic power ram, all contained within the same unit, dates back to World War II when the Germans employed them in their V1 and V2 rockets and several of their fighter-bomber aircraft. Integrated hydraulic servo actuator packages, which were electrically powered and controlled, were used as the rudder parallel actuator for autopilot directional control on the HE-11, JU-88, ME-110, and DO-17 Luftwaffe aircraft. The success of these servo packages led to the testing of an all-attitude autopilot employing such packages in all three axes. Although these tests were successful and showed great potential because of the reduction in vulnerability they provided, lack of funds prevented further development or production by the Germans. A Siemans unit of this type was tested at Wright Air Development Center as long ago as 1950.

This technique has been successfully applied for thrust vector control on missiles. Figure 16 shows a typical missile servo actuator package which consists of an electrically driven motor, hydraulic pump, accumulator, reservoir, servo valve and hydraulic power ram, all contained within the same unit and weighing about 22 pounds. It is a simple, non-redundant, short life system which would be unsuitable for direct application to aircraft use. It does, however, demonstrate that this technique is within the present state-of-the-art. The aileron, elevator and rudder actuators on the VC-10 are an example of the use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of this technique on current aircraft. Eleven similar units are used on split control surfaces--two split ailerons (4), three rudders (3), and two split elevator surfaces (4). Redundancy is thus achieved right out to the control surface, although each individual package is itself non-redundant. An example of the use of a redundant integrated package is on the spoilers of the Belfast where a duplex integrated hydraulic servo actuator package is employed. Since these electrically powered units are completely self-contained and relatively easy to remove and replace, the aircraft down time due to maintenance and repair is significantly shortened. Programs which are now underway at the Air Force Flight Dynamics Laboratory will develop and flight test demonstrate redundant integrated hydraulic servo actuator packages for use in high performance tactical fighter-bomber aircraft (See Figure 6).

Current AFFDL Fly-by-Wire Programs

The fly-by-wire effort of the Control Elements Branch, Flight Control Division, Air Force Flight Dynamics Laboratory is divided into two parts: an in-house effort being conducted in the Control Techniques Laboratory in Building 195 by Hydraulic Research and Manufacturing Company personnel working under contract; and two contracted efforts (facetiously referred to as our out-house efforts) with Douglas-Long Beach and Sperry Pheonix Company.

In-House Programs

The in-house program consists of the design, manufacture, assembly, and flight test of a single axis (pitch) fly-by-wire flight control system for a B-47 aircraft. This program is being accomplished in the following three phases:

Phase I - The existing B-47 control stick and feel system was used in conjunction with a simple nonredundant fly-by-wire system. Linear displacement transducers (LVDT's) connected to the pilot's control stick operated a servo actuator (modified B-47 actuator) in parallel with the existing aircraft pitch actuator. During tests of the fly-by-wire system, the normal aircraft pitch actuator was bypassed. Over 40 flight hours were flown without a failure or malfunction in the fly-by-wire system. The test pilots observed an appreciable improvement in aircraft response to rapid inputs at high "q" flight conditions. The lag in the normal system could be attributed to aircraft cable stretch which, of course, was eliminated when using the fly-by-wire system.

Phase II - A side-stick controller was installed in the pilot's cockpit and a C* feedback system was installed to provide the necessary feel/response. The same nonredundant servo actuator as was used in Phase I was used here. Flight tests are currently being conducted on this system.

Phase III - The side-stick controller and C* feedback system from Phase II will be used but with a quadruply redundant actuator installed in place of the nonredundant servo actuator from Phase I. This actuator will use hydraulic logic and will be powered by four 3,000 psi hydraulic power supplies installed in the tail section of the aircraft.

Throughout this in-house effort, extensive use is being made of the unique facilities of the AFFDL Fly-by-Wire Development Laboratory. By designing, installing and laboratory testing the fly-by-wire systems on the B-47 tail section shown in Figure 17 prior to aircraft installation, much aircraft down time is being avoided. Figure 18 shows the test aircraft during one of its fly-by-wire test flights.

The Douglas Effort

This consists of the completion of an extended program in which much effort was expended in an attempt to design and build a pure electrical (nonelectronic) a.c. primary flight control system. This task, as originally directed by AFFDL, proved impractical and the program was then redirected to permit the use of electronics and d.c. in an effort to obtain more positive results from the remaining resources. A breadboard model of a triply redundant fly-by-wire system was designed and built.

The Sperry Phoenix Effort

This consists of: (1) a fly-by-wire study and research contract, the results of which are included in Technical Report AFFDL-TR-67-53, "Fly-by-Wire Techniques", prepared by Mr. F. L. Miller and Mr. J. E. Emfinger of the Sperry Phoenix Company under the direction of Mr. V. R. Schmitt and F/L J. P. Sutherland, Project Engineers, FDCL, AFFDL: and (2) a recently completed contract to design and build a three-axes, quadruply redundant experimental laboratory model of a fly-by-wire system for a B-47 aircraft. This system, which is shown in Figure 19, is currently being used in the AFFDL Fly-by-Wire Development Laboratory as a design tool for future fly-by-wire flight control system development.

Future Efforts

AFFDL's future programs in fly-by-wire include a program for the flight test demonstration of a complete three-axis, two-fail/operate (quadruply redundant) fly-by-wire flight control system employing redundant integrated hydraulic servo actuator packages, on a tactical fighter aircraft. This two year program is scheduled to begin in early 1969.

Summary and Conclusions

Simple direct mechanical linkages, cables, and feel springs for manual control can no longer cope with many of the control system problems associated with modern high performance aircraft and aerospace

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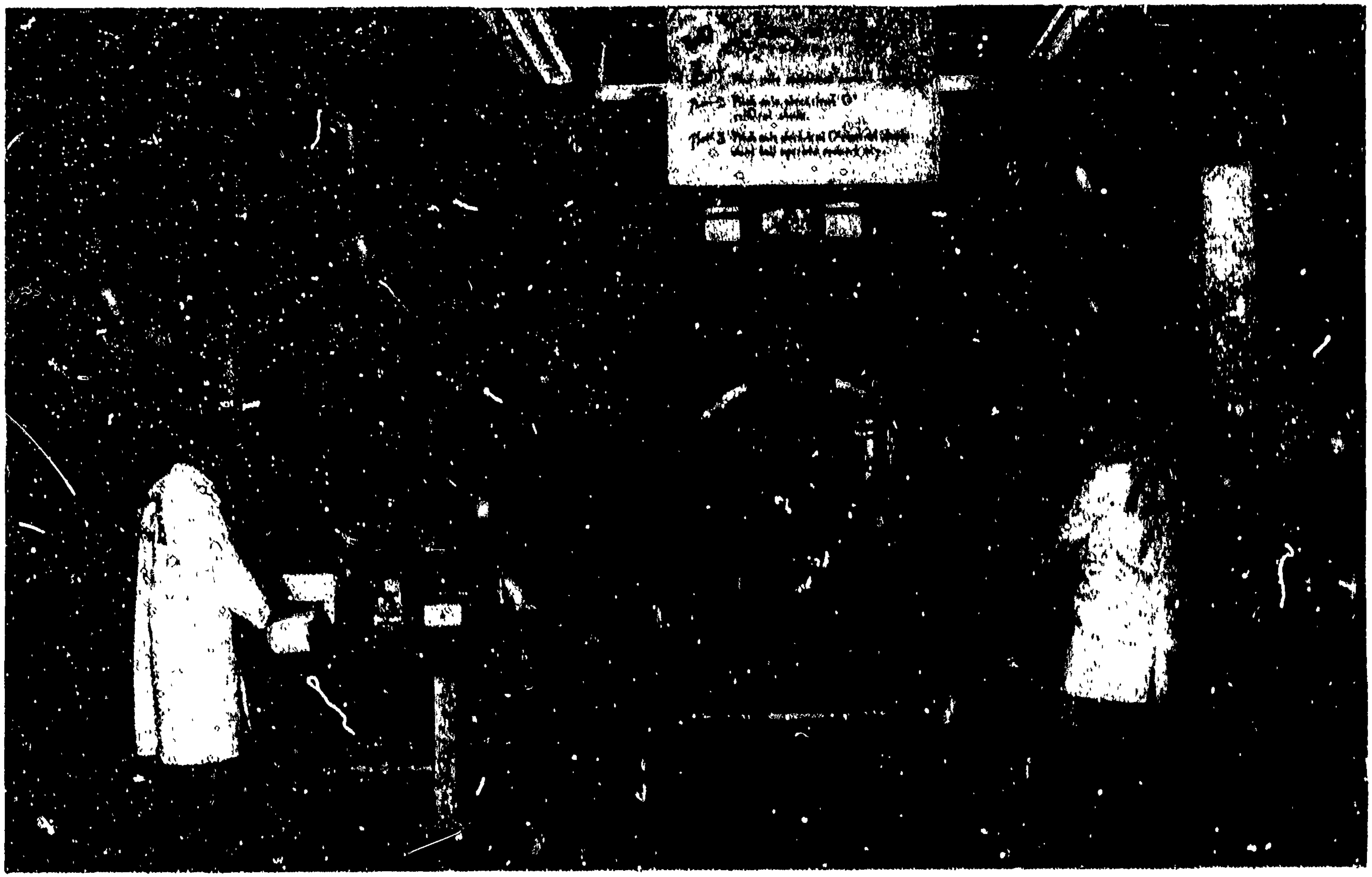


Laboratory Tests of Fly-by-wire Equipment
Using B-47 Tail Section at AFFDL

FIGURE 17

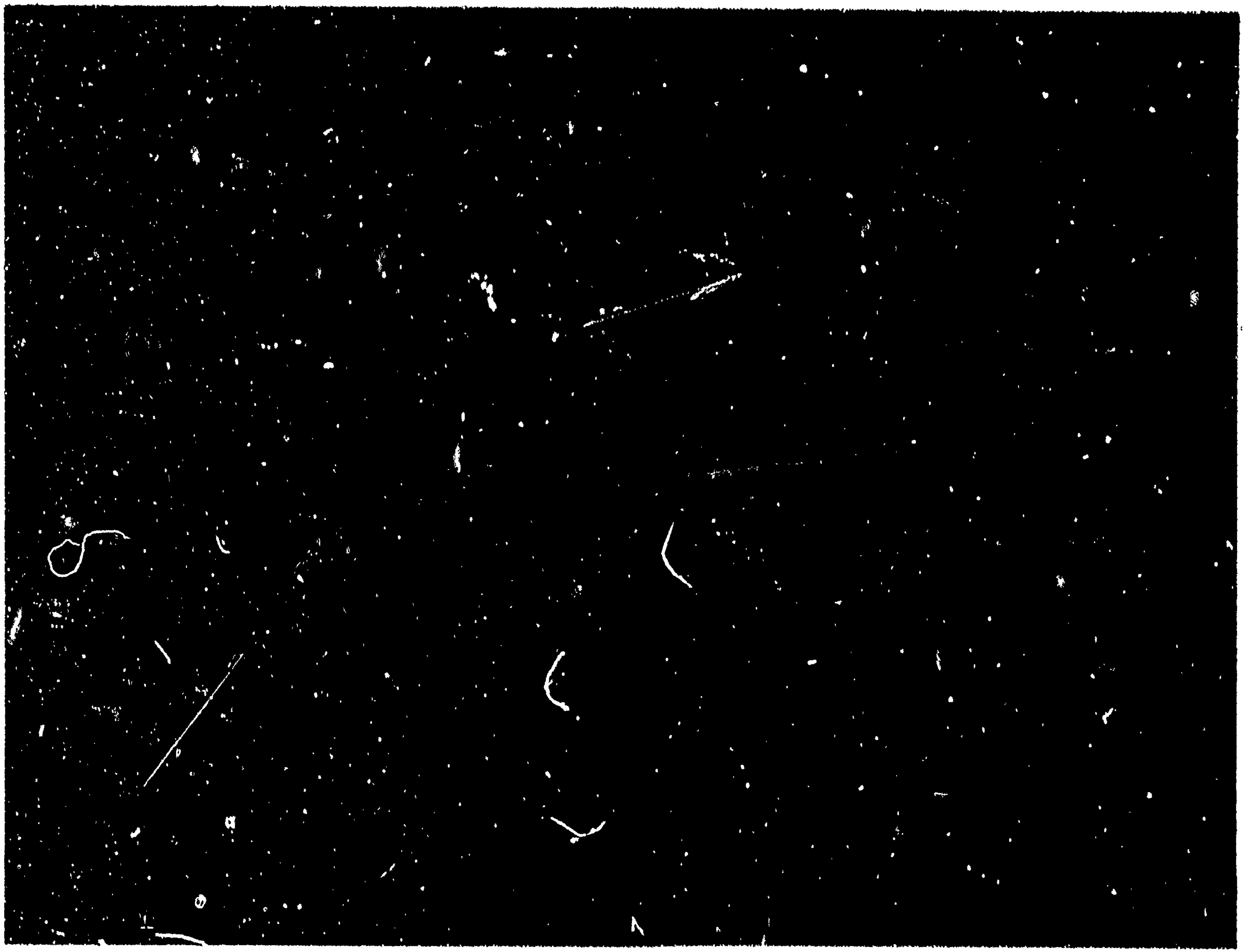
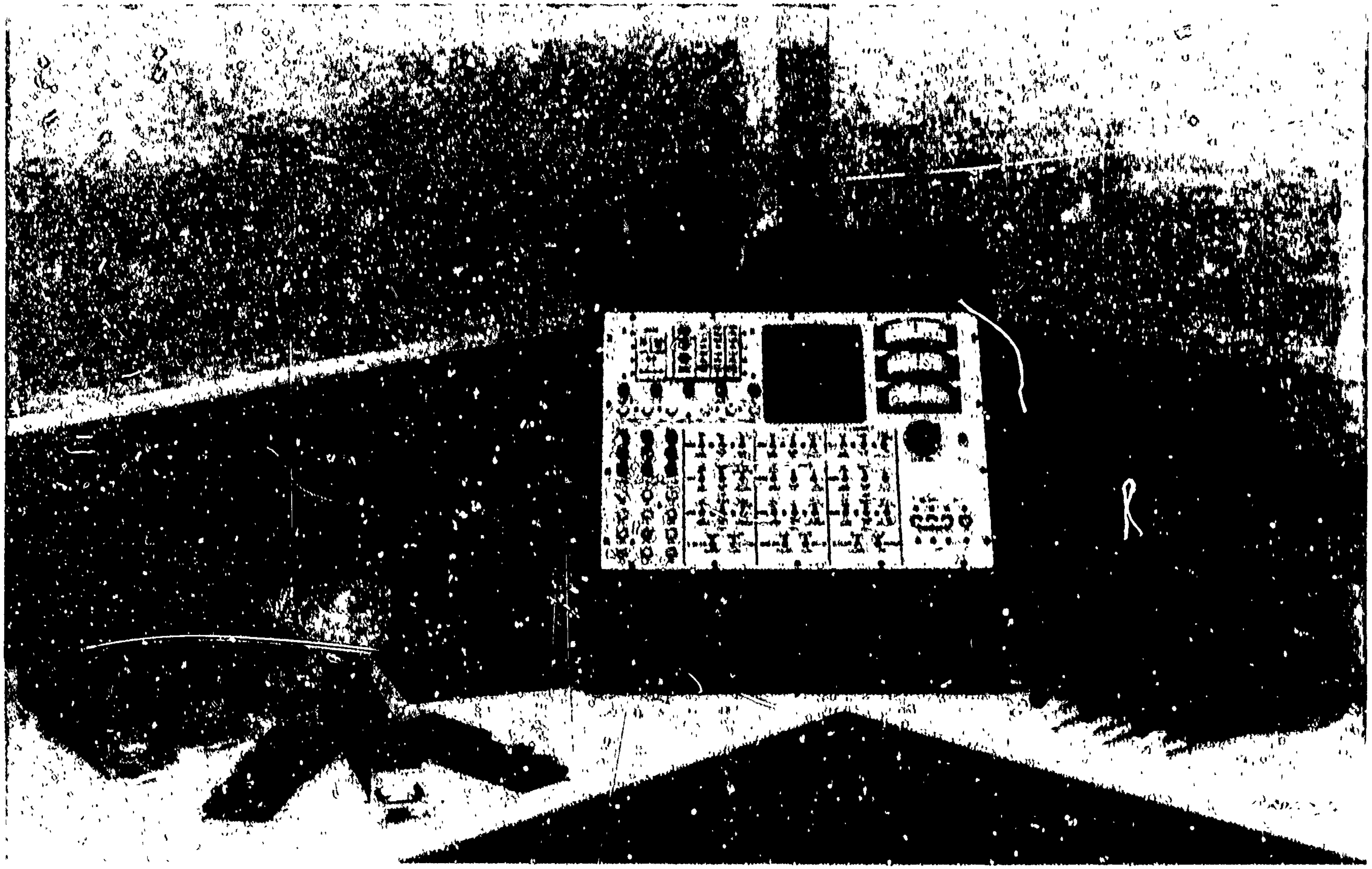


FIGURE 18



Laboratory Model of Quadruply Redundant Fly-By-Wire System.

Built by Sperry Phoenix Co.

FIGURE 19

vehicles. In an effort to meet the greater demands of these advanced aircraft control system requirements, the flight control designer has been forced to increase the complexity of the mechanical system with a resulting increase in weight, volume, and cost, and a decrease in flexibility and reliability. Invariably he is forced to compromise between the desired performance and design requirements and a practical mechanization. Fly-by-wire offers not only to meet the demands of these advanced control system design requirements, but also promises to do so with a decrease in complexity, weight, volume, and cost and an increase in flexibility and reliability. Why then is fly-by-wire not in common use today? The answer to this question was given in the first part of this paper; i.e., a lack of confidence in the concept of fly-by-wire and a feeling of false security in mechanical flight control systems. These are the principal factors which are now retarding the growth and general acceptance of fly-by-wire. The Air Force Flight Dynamics Laboratory fly-by-wire programs are aimed at establishing the assurance level or level of confidence in fly-by-wire control systems among military operators and aircraft manufacturers and designers which is necessary to overcome this stigma. We recognize the inevitable existance of many engineering problems which must be solved in going from a drawing board design to flight worthy hardware. Although our programs will not necessarily establish the best solutions to these problems, they should demonstrate conclusively that the solutions are feasible and practicable. We firmly believe that fly-by-wire is not only inevitable for use in advanced military and commercial aircraft and aerospace vehicles but is, in fact, on the immediate horizon. If this paper has helped to convince you of this fact, or even encouraged you to re-evaluate your previously held opinions, then it has served its purpose well.

Oh Ye of little Faith,
Be still and know,
The era of Fly-By-Wire has come

Paul 9-3

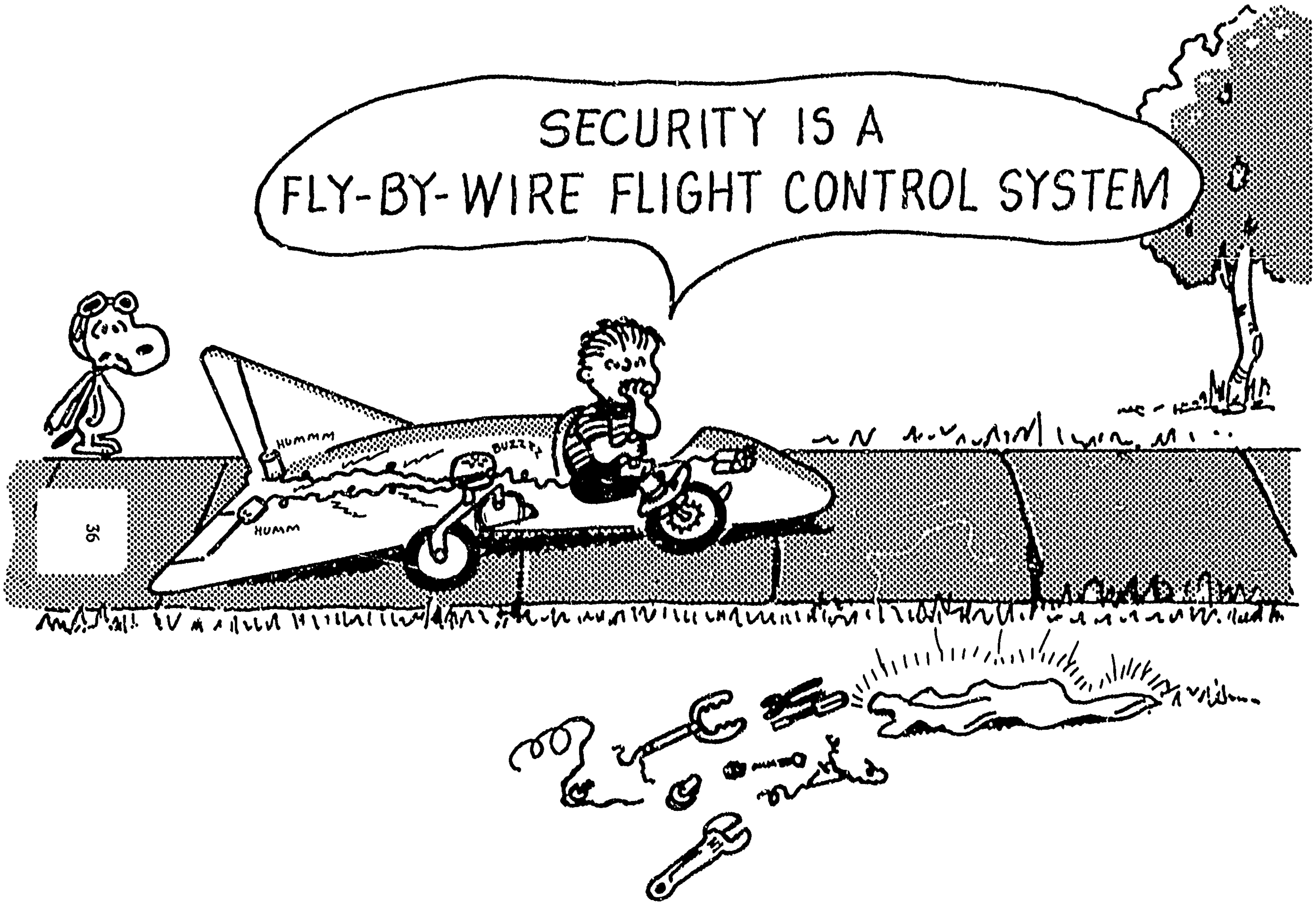

SECURITY IS A FLY-BY-WIRE FLIGHT CONTROL SYSTEM
HUMMM
BUZZZ
HUMM

FIGURE 20

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