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STOL TACTICAL AIRCRAFT INVESTIGATION– EXTERNALLY BLOWN FLAP

Volume V

Flight Control Technology

Part I

Control System Mechanization Trade Studies

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FOREWORD

This report was prepared for the Prototype Division of the Air Force Flight Dynamics Laboratory by the Los Angeles Aircraft Division, Rockwell International. The work was performed as part of the STOL tactical aircraft investigation program under USAF contract F33615-71-C-1760, project 643A0020. Daniel E. Fraga, AFFDL/PTA, was the Air Force program manager, and Garland S. Oates, Jr., AFFDL/PTA, was the Air Force technical manager. Marshall H. Roe was the program manager for Rockwell.

This investigation was conducted during the period from 10 June 1971 through 9 December 1972. This final report is published in six volumes and was originally published as Rockwell report NA-72-868. This report was submitted for approval on 9 December 1972.

This technical report has been reviewed and is approved.

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ABSTRACT

The basic objective of the work reported herein was to provide a broader technology base to support the development of a medium STOL Transport (MST) airplane. This work was limited to the application of the externally blown flap (EBF) powered lift concept.

The technology of EBF STOL aircraft has been investigated through analytical studies, wind tunnel testing, flight simulator testing, and design trade studies. The results obtained include development of methods for the estimation of the aerodynamic characteristics of an EBF configuration, STOL performance estimation methods, safety margins for takeoff and landing, wind tunnel investigation of the effects of varying EBF system geometry parameters, configuration definition to meet MST requirements, trade data on performance and configuration requirement variations, flight control system mechanization trade data, handling qualities characteristics, piloting procedures, and effects of applying an air cushion landing system to the MST.

From an overall assessment of study results, it is concluded that the EBF concept provides a practical means of obtaining STOL performance for an MST with relatively low risk. Some improvement in EBF performance could be achieved with further development - primarily wind tunnel testing. Further work should be done on optimization of flight controls, definition of flying qualities requirements, and development of piloting procedures. Considerable work must be done in the area of structural design criteria relative to the effects of engine exhaust impingement on the wing and flap structure.

This report is arranged in six volumes:

Volume I - Configuration Definition

Volume II - Design Compendium

Volume III - Performance Methods and Takeoff and Landing Rules

Volume IV - Analysis of Wind Tunnel Data

Volume V - Flight Control Technology

  Part I - Control System Mechanization Trade Studies
  Part II - Simulation Studies/Flight Control System Validation
  Part III - Stability and Control Derivative Accuracy Requirements and Effects of Augmentation System Design

Volume VI - Air Cushion Landing System Trade Study

This Volume, V, Part I, presents the results of trade studies of five means of mechanization of the flight control system:

- Mechanical
- Mechanical plus stability augmentation (SAS)
- Mechanical plus control and stability augmentation (CASAS)
- Fly-by-wire with mechnical backup
- Fly-by-wire

The fly-by-wire mechnical backup system was found to be most suitable for application to the MST. This mechanization met all system requirements, and while heavier by 694 pounds than its nearest competitor, it did possess the lowest system failure rate.

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LIST OF SYMBOLS

Parameter	Definition	Units
δ_e	Elevator deflection	Degrees
δ_h	Horizontal stabilizer deflection	Degrees
δ_s	Spoiler deflection	Degrees
δ_A	Aileron deflection	Degrees
δ_R	Rudder deflection	Degrees
ϕ	Bank angle	Degrees
θ	Pitch angle	Degrees
F_{th}	Pilot trim force	Pounds
F_{PR}	Pilot input roll force (wheel or stick)	Pounds
F_{PY}	Pilot input yaw force (pedals)	Pounds
F_{PP}	Pilot input pitch force (column or stick)	Pounds

ACRONYMS

MST	Medium STOL transport
STOL	Short takeoff and landing
EBF	Externally blown flap
CASAS	Control and stability augmentation system
SAS	Stability augmentation system
DLC	Direct lift control
LVDT	Linear variable differential transformer
P_F	Failure probability
K	Gain
CG	Center of gravity

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SECTION I

INTRODUCTION

The selection of the most suitable flight control system mechanization for an MST aircraft should depend on trade-off studies specifically related to the MST and its particular problems, but in addition, selection of concepts and mechanization techniques will depend on company experience and knowledge of advanced controls technologies and data available throughout the Air Force and industry. Rockwell International gained a wealth of experience and design capability during the XB-70 design and test program. Much of the technology gained is still directly applicable to MST controls design problems. Designs that allow for sustained operation in high temperature environments and designs for fail-safe augmentation servos are examples of important technology that can carry over to an MST. Following the cancellation of the Boeing SST program, a review of SST control concepts and hardware was made for applicability to the B-1. This review provided a good background on control concepts and redundancy techniques applicable to a large transport aircraft. This review also provided insight into the degree of complexity involved in providing built-in test capability in a multichannel redundant control system. McDonnell-Douglas, supported by General Electric, LTV, and Sperry, is currently involved in a survivable flight control system program for the Air Force, which is providing valuable fly-by-wire design data. The four-channel redundant augmentation servo could be an important element for fly-by-wire systems. This program further emphasized the importance of built-in test equipment to the success of fly-by-wire systems.

The technology advances being made in the development of the B-1 should have considerable applicability in the development of an MST. The B-1 must satisfy stringent flying qualities requirements while operating over a wide range of mach, altitude, wing position, weight and CG conditions. Also, stringent mission success and flight safety reliability requirements have been imposed. Systems developed to satisfy these requirements certainly provide concepts and elements for strong consideration in an MST. The summation of the technology advances that have been made over recent years provides an excellent background for the development of a flight control system specifically applicable to an MST aircraft.

Throughout the history of flight, control system weight and reliabilities have become increasingly important in system configuration definition. This is especially true in the more modern days of STOL aircraft, because of the increased complexity of, and importance attached to, the control system. The increased dependence on the control systems for performance and safety and the necessary application of technology advances make risk in development another important selection consideration. Cost of the control system is also closely tied to its final selection. Weight, reliability, cost, and risk of development are considered to be the foremost factors that must be traded off in the selection of a control system on the MST. Inherent in this approach is the assumption that all systems provide satisfactory performance during normal operation.

The mechanization of the control system for the MST involves the control of spoilers and ailerons for roll, the horizontal stabilizer and elevator for pitch, plus the inner two spoiler panels for direct lift control, and the vertical stabilizer for yaw control. These aerodynamic control surfaces plus their actuation systems and the cockpit controls become a fixed part of any control system to be evaluated. This leaves the interconnecting portion of the system to be developed, and trades must be made among the alternate systems.

SECTION II

SYSTEM ANALYSES

BASIC GROUND RULES

With the MST, as with all other aircraft, the requirements on degree and reliability of augmentation are determined by the bare airframe flying qualities. The MST's bare airframe handling qualities are such that control and stability augmentation are required to provide Level 1 handling qualities during STOL operations. For this mode of flight handling qualities, parameters were evaluated relative to specification requirements (refer to section V, part 2) to insure that an adequate augmentation system was included for mechanization comparisons. Roll and yaw augmentation are required to provide Level 1 flying qualities during conventional flight, and roll, yaw, and pitch augmentation are required to provide Level 1 flying qualities during STOL flight. Level 2 flying qualities are provided during conventional flight, and Level 3 flying qualities are provided during STOL flight with the loss of all augmentation. The ground rules relative to Levels 2 and 3 for STOL operation are based on simulation tests. (Reference to Volume V, Part 2, "Flight Simulation Studies," of this final report.) Ground rules relative to conventional flight are based on previous analysis and experience.

The aircraft hydraulic and electrical system design is also governed by the requirements of the flight control system. These requirements are that loss of one hydraulic or electrical system shall not cause reversion to Level 2 flying qualities, and that loss of two hydraulic or two electrical systems shall not cause reversion to worse that Level 3 flying qualities. This is because of the comparatively high failure rates of these systems, and the desire not to have a failure of a hydraulic or electrical system result in a degradation of flying qualities. In addition to the restriction of degradation of flying qualities with losses of hydraulic supplies, there are also restrictions against degradation of flying qualities with any combination of failures. These restrictions are found in MIL-F-8785B, which states the probability of encountering Level 2, as a result of a combination of failures should be less than 10^{-2}, per mission, and that the probability of reversion to Level 3 should be less than 10^{-4} per mission. Not found directly in MIL-F-8785B, are the requirements for loss of the flight control system. This is a goal for loss of control of the aircraft chargeable to the flight system. For the B-1 aircraft, this goal was set at about 2.0×10^{-5} for a 5-hour mission. For the MST, being a transport aircraft, it was felt that a probability goal somewhat lower should be chosen. This is because of the probability of having passengers aboard with no escape system provided. A goal of 10^{-5} for a 5-hour mission was chosen. This is a goal that is not covered by any military specification; however, it is felt that it will be applicable as a transport flight control systems goal during the 1970's. Along with these restrictions are the somewhat relieving conditions that Level 3 flying qualities will be provided after the loss of any two roll control spoiler panels or an aileron per wing or the loss of rudder control, with the rudder near neutral.

The air vehicle flying qualities and flight safety requirements that set the ground rules for a control system mechanization study are summarized as follows:

1. Loss of one hydraulic or electrical system shall not cause reversion to Level 2 flying qualities.

2. Loss of two hydraulic or two electrical systems shall not cause reversion to worse than Level 3 flying qualities.

3. The probability of any combination of failures causing reversion to Level 2 flying qualities in any axis shall be less than 10^{-2} for a 5-hour mission.

4. The probability of any combination of failures causing reversion to Level 3 flying qualities in an axis shall be less than 10^{-4} for a 5-hour mission.

5. The probability of any combination of failures causing an unsafe control condition shall be less than 10^{-5} for a 5-hour mission.

6. During STOL mission phases the pitch, roll, and yaw axes of control and stability augmentation are required to provide Level 1 flying qualities, and roll and yaw augmentation are required to provide Level 2 flying qualities.

7. During conventional flight, roll and yaw axes of augmentation are required to provide Level 1 flying qualities. Level 2 flying qualities are provided with loss of all augmentation.

8. Level 3 flying qualities are provided in all mission phases with the loss of any two roll control spoiler panels or an aileron per wing, and the loss of all rudder control with the rudder near neutral.

BASIC POWER ACTUATION SYSTEM

The basic end point of any control system mechanization is the controlled deflection of the aerodynamic control surfaces. With an air vehicle in the

150,000-pound class, and with the requirement for comparatively light control forces, powered surface actuation is considered a basic control system requirement. This basic actuation system will be common to any control system mechanization. Also common to any control system mechanization will be the pilot and copilot cockpit controls, consisting of rudder pedals, control column and wheel, and trim controls. Since any control system mechanization includes these elements, their weights and reliabilities will be a part of all mechanizations evaluated.

Figure 1 presents a simplified reliability diagram of a single-surface actuator and its hydraulic power supply. The numbers shown in the blocks indicate failure rates per million flight hours. The failure rates are in series, and one failure will cause loss of control. The net rate is 0.622 unsafe conditions per 10^3 flight hours, or a potentially major accident every 1600 flying hours due to this single portion of the control system. This is obviously unacceptable, and redundancy is required. The air vehicle hydraulic systems are not considered part of the air vehicle flight controls systems, but the requirements of the flight controls, and other systems, do set the hydraulic system redundancy requirements. The air vehicle has four-engines, and each engine may provide an independent hydraulic system. The reliability of each system may be increased by providing each system with dual pump systems, thereby greatly reducing the failure probability of this portion of the system. Pump duality will reduce the failure rate of this portion of the system to about 0.054×10^{-6} per flight hour; this does not account for engine failures, or the parts of the system where duality can not help. These parts are the reservoirs and series components such as plumbing lines. This leaves a hydraulic system failure rate of about 3.65×10^{-4} per flight hour, providing a clear requirement for redundant systems. Supplying a single actuator with dual hydraulic supplies is not practical and, since a single actuator system would cause a major accident about every $41 \times 10^{+3}$ flight hours, redundant actuators are also a requirement. To insure retention of at least Level 3 flying qualities after two hydraulic system failures for any reason, including engine failures, a minimum of three actuators, each powered by an independent hydraulic system are required. Figure 2 presents a simplified reliability diagram of a triple actuation system with dual feedback and input control linkages. For a flight time of 5 hours, triple redundancy of the actuators and hydraulic power supplies essentially precludes loss of control, except for those failures classified as jams. These are failures which cannot be unjammed with all available force, and result in a locked control surface. The failure probability for a 5-hour flight is about 0.3×10^{-6}.

Figure 3 presents the 5-hour mission failure probability block diagram of the fixed portion of the control system, the control surface power actuation subsystem. In this type of representation, any continuous path through the diagram represents a situation in which no combination of

(233 + 365 + 1.5 + 22.5 + .02) X 10^{-6}/HR ≈ 622 FAILURES PER MILLION FLIGHT HOURS OR ONE FAILURE EVERY 1,600 FLIGHT HOURS

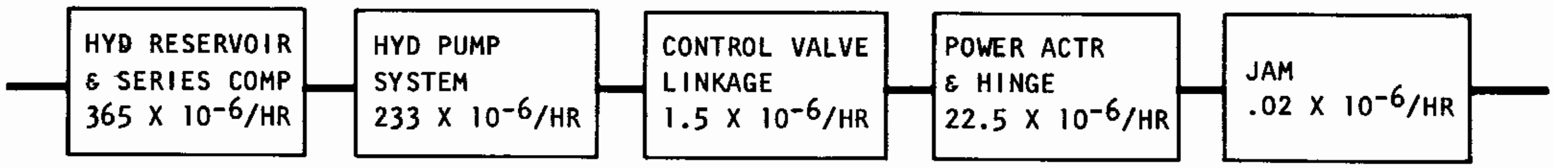
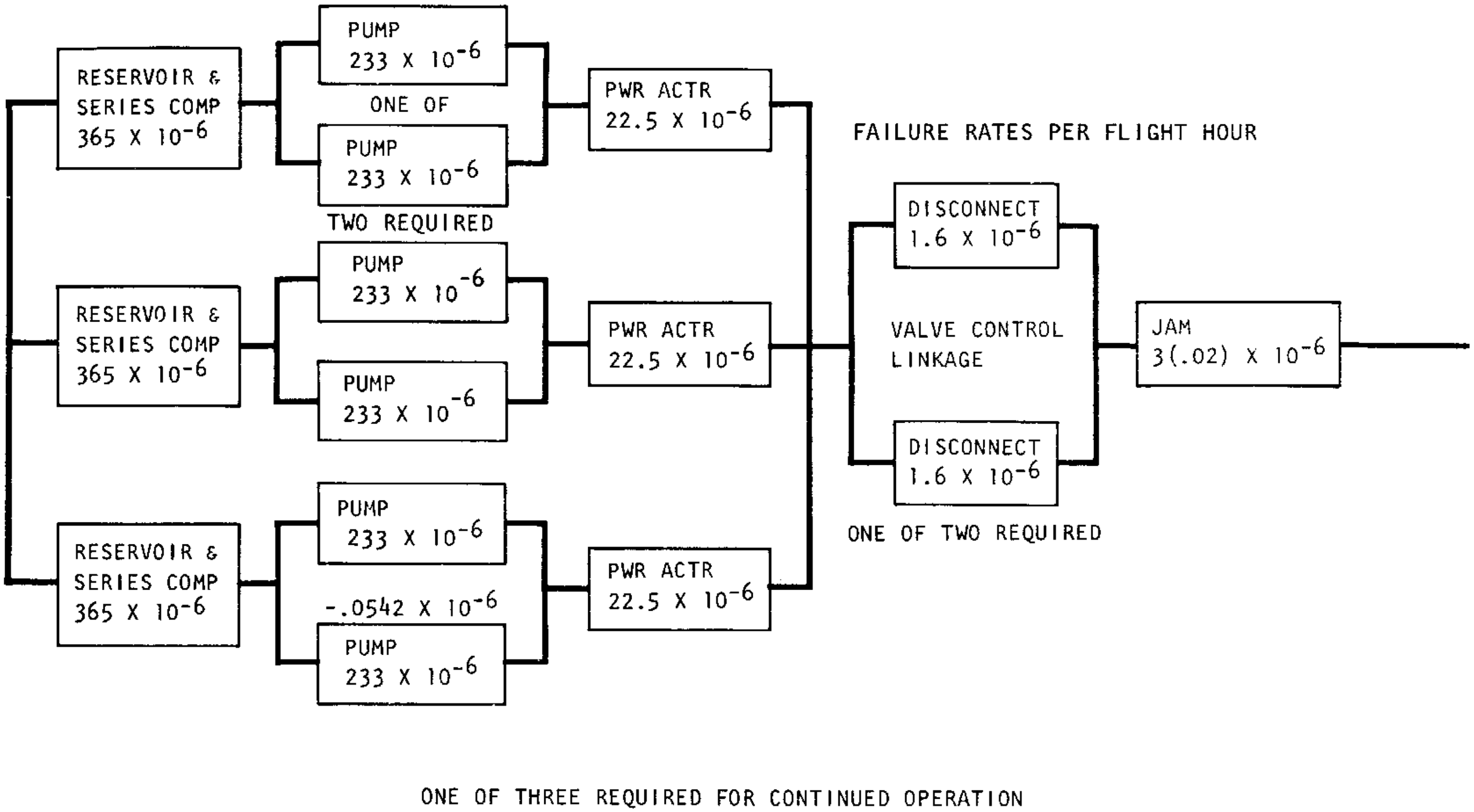


Figure 1. Single Power Actuation Failure Probability



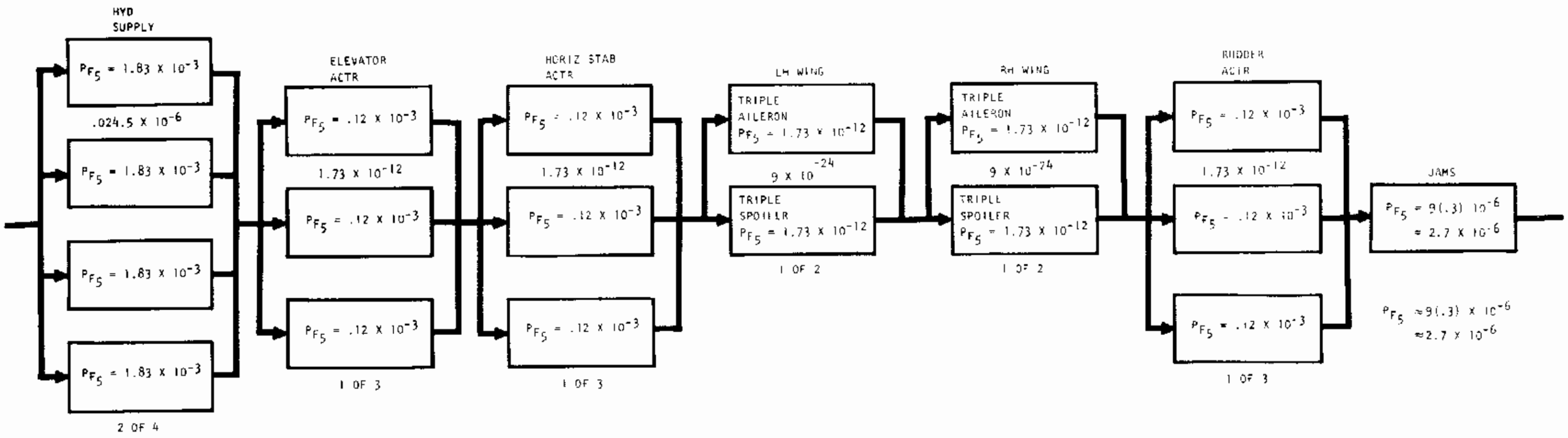
NET FAILURE PROBABILITY $\approx (365 \times 10^{-6}/\text{HR} + .0542 \times 10^{-6}/\text{HR}^2 + 22.5 \times 10^{-6}/\text{HR})^3 + (1.6 \times 10^{-6}/\text{HR})^2 + .06 \times 10^{-6}/\text{HR}$

$\approx 58 \times 10^{-12}/\text{HR}^3 + .161 \times 10^{-15}/\text{HR}^6 + 2.56 \times 10^{-12}/\text{HR}^2 + .06 \times 10^{-6}/\text{HR};$

$(.058) \times 10^{-9}(125) + (2.56) \times 10^{-12}(25) + (.06) \times 10^{-6}(5) \approx .3 \times 10^{-6}$ FOR A 5-HOUR MISSION

Figure 2. Triple Redundant Power Actuation Failure Probabilities

FAILURE RATES OF BASIC ACTUATION SYSTEM FOR A 5-HOUR MISSION



$$P_F = 9(0.3)\ 10^{-6} = 2.7 \times 10^{-6}$$

Figure 3. Basic Actuation System Failure Probabilities

failures has resulted in loss of control. The net calculated failure probability is of a failure or combinations of failures causing a discontinuity in the chain. The roll portion of the system is shown in parallel because of the ground rule that safe control can be maintained with the loss of an aileron or two spoiler panels per wing. Yaw control is also shown in series; however, it may well be argued that a safe landing could be made without yaw control. The loss of Level 1 flying qualities probabilities calculations due to failures in these parts of the system are the same as the unsafe flight probability calculations, except all of the roll control has been placed in series.

Figure 4 presents a schematic of the power actuation system. The resultant unsafe failure probability of 2.7 x 10^{-6} for a 5-hour mission sets a goal of no more than 7.3 x 10^{-6} for the signal transmission trade study candidates. The loss of Level 1 flying qualities possibility of 2.7 x 10^{-6} sets a goal of 10^{-2} for these systems.

The control surface power actuation system estimated weights are presented herein. These weights present a basis for comparison of the deltas added by the trade candidates. The weight of the cockpit controls is included here, while the reliability of these elements is included in the paragraphs on the mechanical system.

• Horizontal stabilizer	Three single actuators, including valves, dual control linkage, and plumbing, 68 lb (3).	204 lb
• Elevator	Three actuators	152 lb
• Rudder	Three actuators	152 lb
• Ailerons	Six actuators	328 lb
• Roll spoilers	Six actuators	328 lb
• Direct lift control	Six actuators	328 lb
• Cockpit controls	Two sets	160 lb
	Total	1,652 lb

CONTROL SYSTEM SIGNAL TRANSMISSION

MECHANICAL SYSTEM

The first control system trade candidate is a pure mechnical system connecting the pilot's cockpit control columns, wheels, and rudder pedals to the aerodynamic control surface power actuation systems. It is a set of single systems consisting of the bellcranks, pushrods, cable runs, and

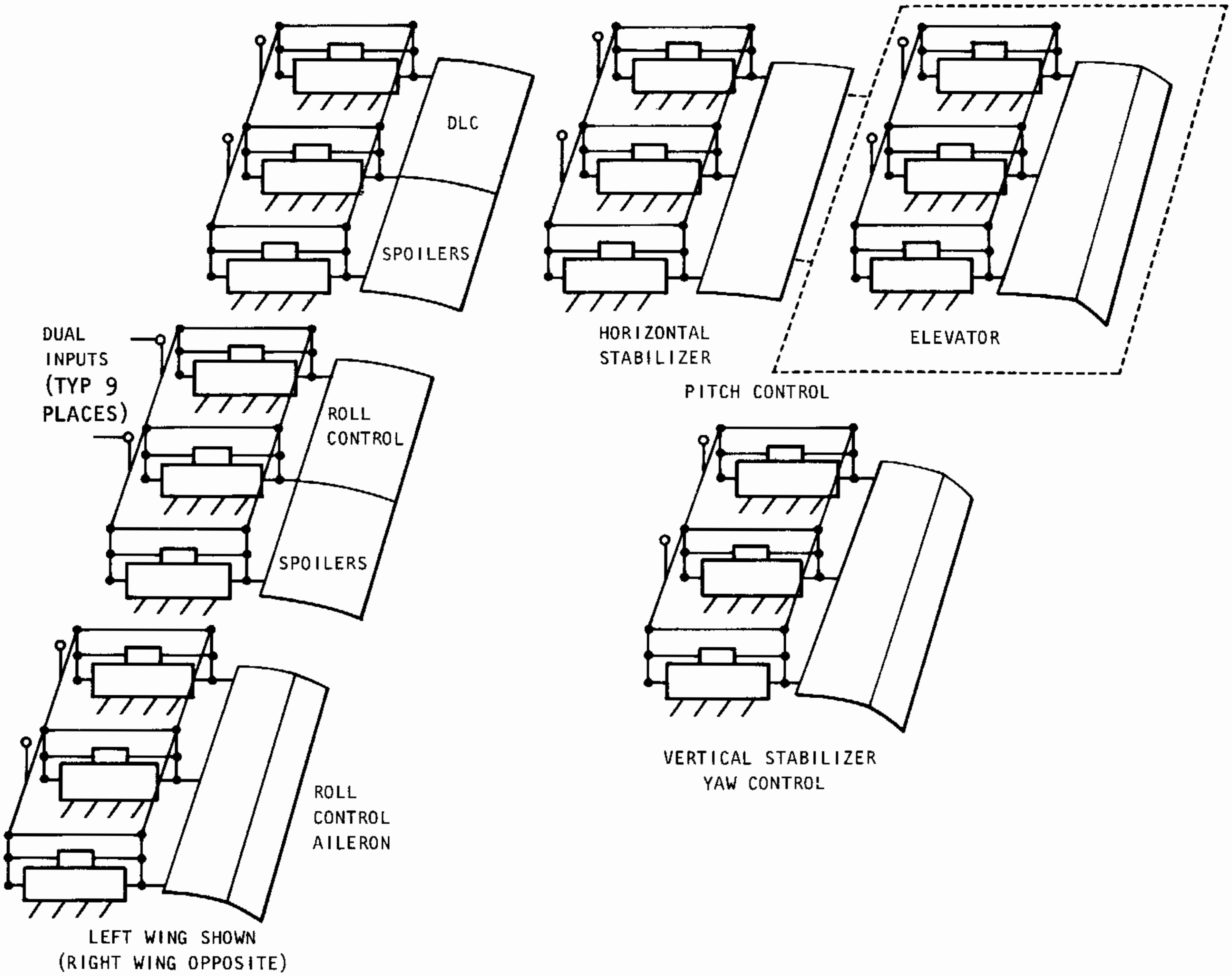


Figure 4. Triple Redundant Power Actuation Subsystem

pulleys that connect the cockpit controls to the appropriate input control linkages of the power actuation system. It also supplies artificial-feel and trim in all axis. Figure 5 presents simplified schematics of the system, along with lumped system disconnect and jam failure rates per million flight hours. The rates used are typical of these classes of mechanical components.

The pitch cable run is connected through pushrods to the cockpit control columns. It is tapped near the aircraft's center and runs are supplied, through a washout, to the input control linkage of the power actuation system for the direct lift control (DLC), inner two spoiler panels in each wing. A cable tension regulator bungee is located at the terminal of the cable system near the tail. At this point, the cable system is divided into two functions. One function controls the elevator power actuator input linkages through a flap gearing mechanism, and the other function controls the horizontal stabilizer power actuator input linkages through a different flap gearing mechanism. Primary trim is supplied by an electrical trim actuator controlled by "coolie-hat" switches on the control wheels. Standby trim is provided by means of a trim wheel located on the center console mechanically in parallel with the trim actuator gearing. Secondary power switches are provided to cut power to the trim actuators to provide protection against runaway trim.

The roll cable system is connected through pushrods to the control wheels. At a central point, the system is divided into right- and left-hand wing control functions. Cable tension regulation is provided at this point. The right- and left-hand control functions feed out through the wing to control the outboard two spoiler panels and aileron power actuation system input control linkages. Trim and feel are as described for the pitch system. Pitch and roll primary trim share the coolie-hat trim switches located on the pilot and copilot control wheels.

The yaw cable system is connected to the rudder pedals by means of pushrods. The cable system runs to the tail section where cable tension regulation is provided. The output of the cable system is connected to the control input linkages of the rudder power actuation system through a flap-controlled limiting function. The limiting function is provided to restrict rudder travel at the higher speed flight conditions.

The yaw system is not included in the major accident probabilities estimates. The yaw system failure probabilities were estimated for flying qualities degradation probability purposes; however, this system will have the probability of the loss of yaw control of 1.6×10^{-5} due to system disconnects. This amounts to loss of yaw control due to all causes of 1.34×10^{-4} for a 5-hour mission.

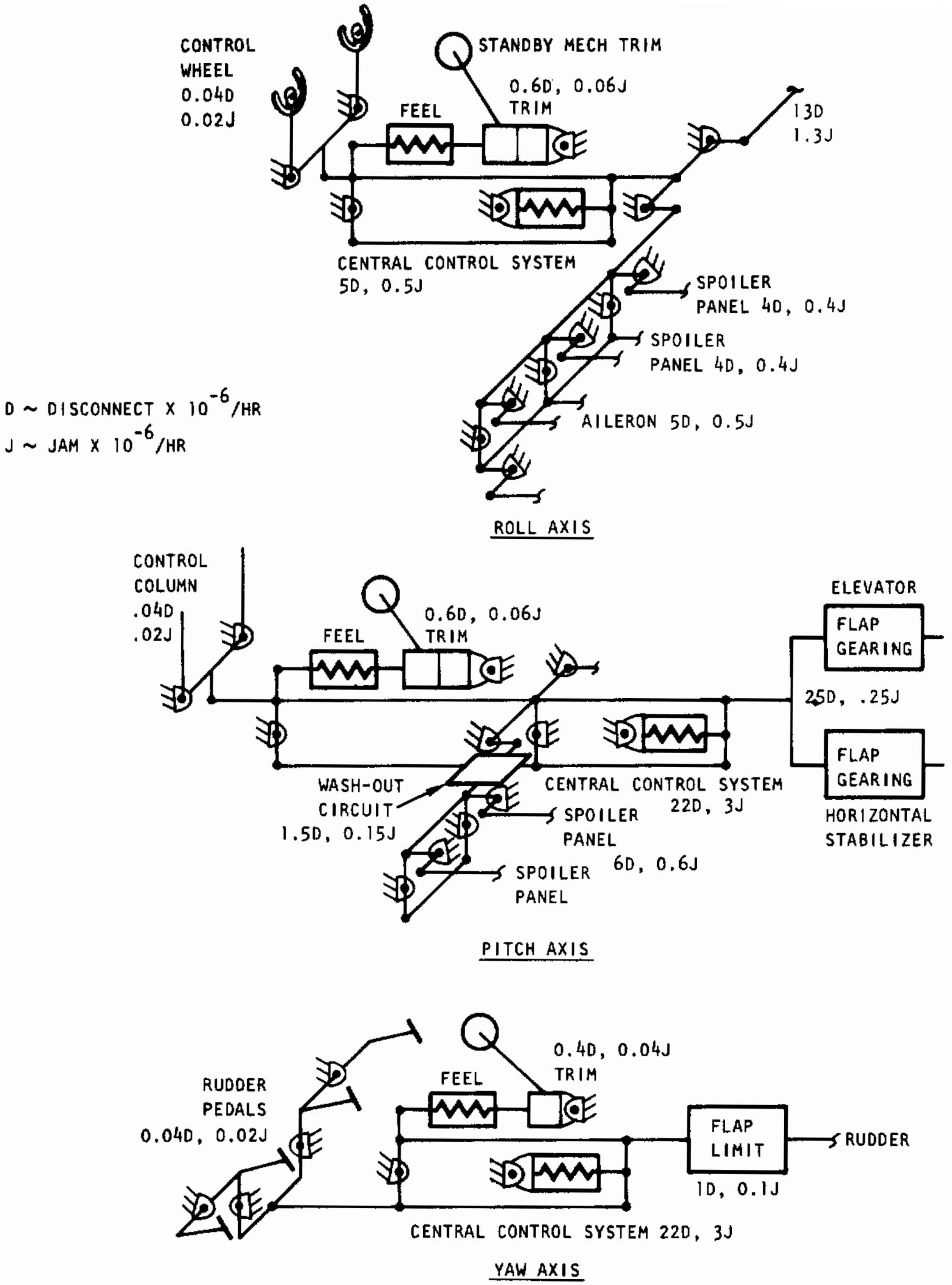


Figure 5. Single Mechanical Control System

Figure 6 presents the lumped parameter failure probabilities of the system. The single mechanical control system flight safety failure probabilities are estimated excluding the yaw axis, and roll ailerons, and pitch DLC, except for jams. This net system has a disconnect failure rate of 4.68×10^{-5} per hour and a jam rate of 7.59×10^{-6} per hour or a net major accident rate of about 5.44×10^{-5} per hour. A 5-hour mission would result in a major accident probability of about 2.72×10^{-4}. This is an unacceptable failure rate. Duality would decrease the loss of control probability due to the rate of disconnects to about 0.002×10^{-6} per hour; however, the jam rate would increase to about 1.52×10^{-5} per hour, and the weight would about double. System duality would result in a major accident rate of 7.6×10^{-5} for a 5-hour mission, and a system weight of about 1,308 pounds for a total of 2,960 pounds.

Level 1 flying qualities will not be supplied. The performance of this system would not meet the flight safety noted in table I. The system performance was developed to provide a basepoint about which stability augmentation could be added in order to meet the flying quality requirements. The system weights are as follows:

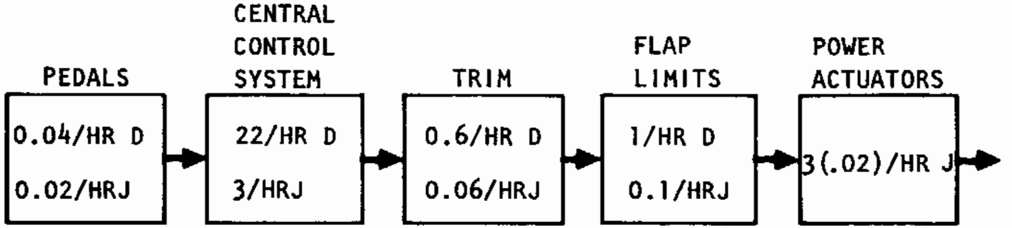
	Pitch	Roll	Yaw
Cable system	109 lb	196 lb	103 lb
Direct lift control	57		
Trim and feel	51	51	33
Flap function	36		38
	253 lb	247 lb	154 lb

System Total = 654 lb

MECHANICAL CONTROL PLUS STABILITY AUGMENTATION

The second system trade study candidate consists of the dual mechanical control system combined with stability augmentation in order to increase the systems performance in the flying qualities areas. The system provides stability augmentation in all axes on a full-time basis. The effects of the stability augmentation feedbacks on control sensitivities are compensated for an increased command path gains provided by gearing changes in the mechanical command paths. Level 1 flying qualities are provided in all axes for both STOL and conventional flight. For the purpose of this study, it

YAW SYSTEM

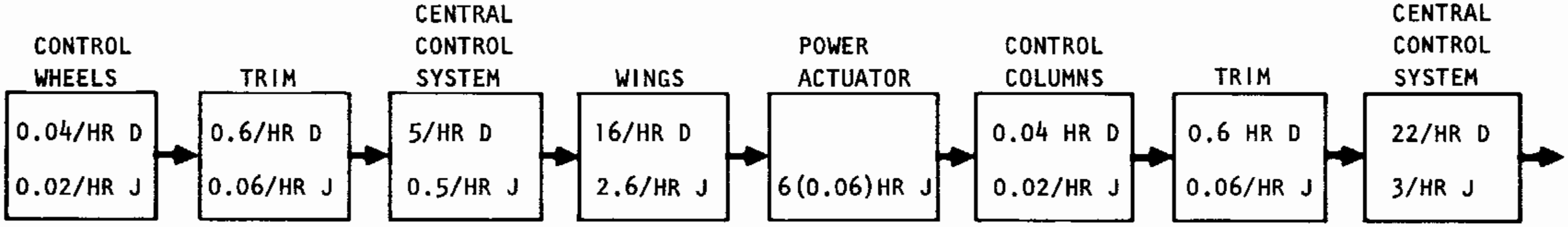


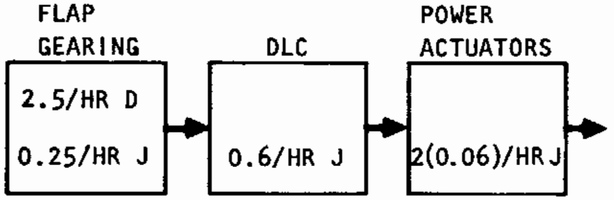
$23.64\text{x}10^{-6}$/HR DISCONNECT

$3.24\text{x}10^{-6}$/HR JAM

$23.64(10^{-6}/\text{HR})(5\ \text{HR}) + 3.24(10^{-6})/\text{HR}\ (5\ \text{HR}) = \overset{D}{118.2\text{x}10^{-6}} + \overset{V}{16.2\text{x}\ 10^{-6}} = 134.4\text{x}10^{-6} = P_F$

ROLL AND PITCH SYSTEMS





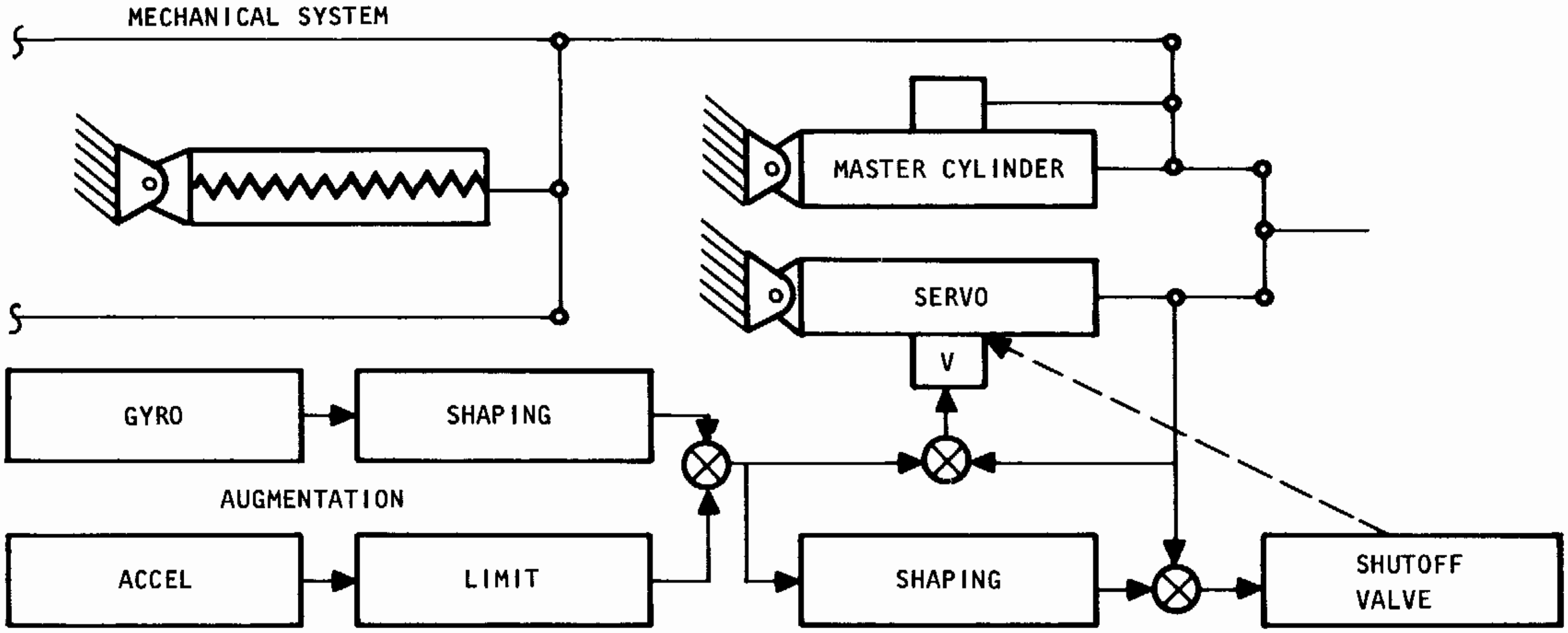
$46.78(10^{-6})$/HR DISCONNECT: $54.37\ (10^{-6}/\text{HR})\ (5\ \text{HR}) = 271.85 \times 10^{-6}$

$7.59\ (10^{-6})$/HR JAM $= P_F$

WITH A DUAL SYSTEM, DISCONNECTS ARE SQUARED AND JAMS ARE DOUBLED

$(46.78)^2 10^{-12}/\text{HR}^2 + 2(7.59)\ 10^{-6}/\text{HR} = 15.2 \times 10^{-6}/\text{HR} \therefore 15.2(10^{-6})/\text{HR}\ (5\ \text{HR}) = 76 \times 10^{-6} = P_F$

Figure 6. Mechanical System Failure Probabilities



RELIABILITY X 10^{-6}/HR

SERVO CYL	2.5	GYRO	35
SERVO VALVE	50.	ACCEL	20
VALVE DRIVER	10.	ELEC	24
PICK OFF	7.5	SHUTOFF VALVE	36
MISC	5.0	MISC	10
	75.0		125

WEIGHT (LB)

SERVO CYL	15
AMP	10
ELEC	10
GYRO	3
ACCEL	3
MISC	12
	53

PITCH AXIS + 2 M/C'S	=	93
YAW AXIS	=	53
ROLL AXIS + 2 M/C'S	=	91
TOTAL		237 LB

Figure 7. Single Servo SAS

is assumed that the aircraft provides four independent electrical systems. These electrical systems are provided for the operation of systems independent of the flight controls system. The added weight to the electrical system by the installation of electrical flight controls was not calculated because it was assumed that it would be the same for all of the systems.

The addition of stability augmentation requires further changes to the basic mechanical control system. Since the damping motions of the augmentation servos will be grounded at the pilot's controls, means must be provided to isolate these controls from objectionable feedback motions. In the yaw system, the comparatively heavier feel bungee control forces and breakout or preload characteristics will provide adequate pilot isolation. The pitch and roll axes have lighter feel and lower breakout forces. Dual tandem master cylinders were added to each of the pitch and roll mechanical control systems, and the stability augmentation servo outputs are summed with the master cylinders to provide control over the power actuation systems. The yaw stability augmentation servo output is directly summed with the yaw cable system output.

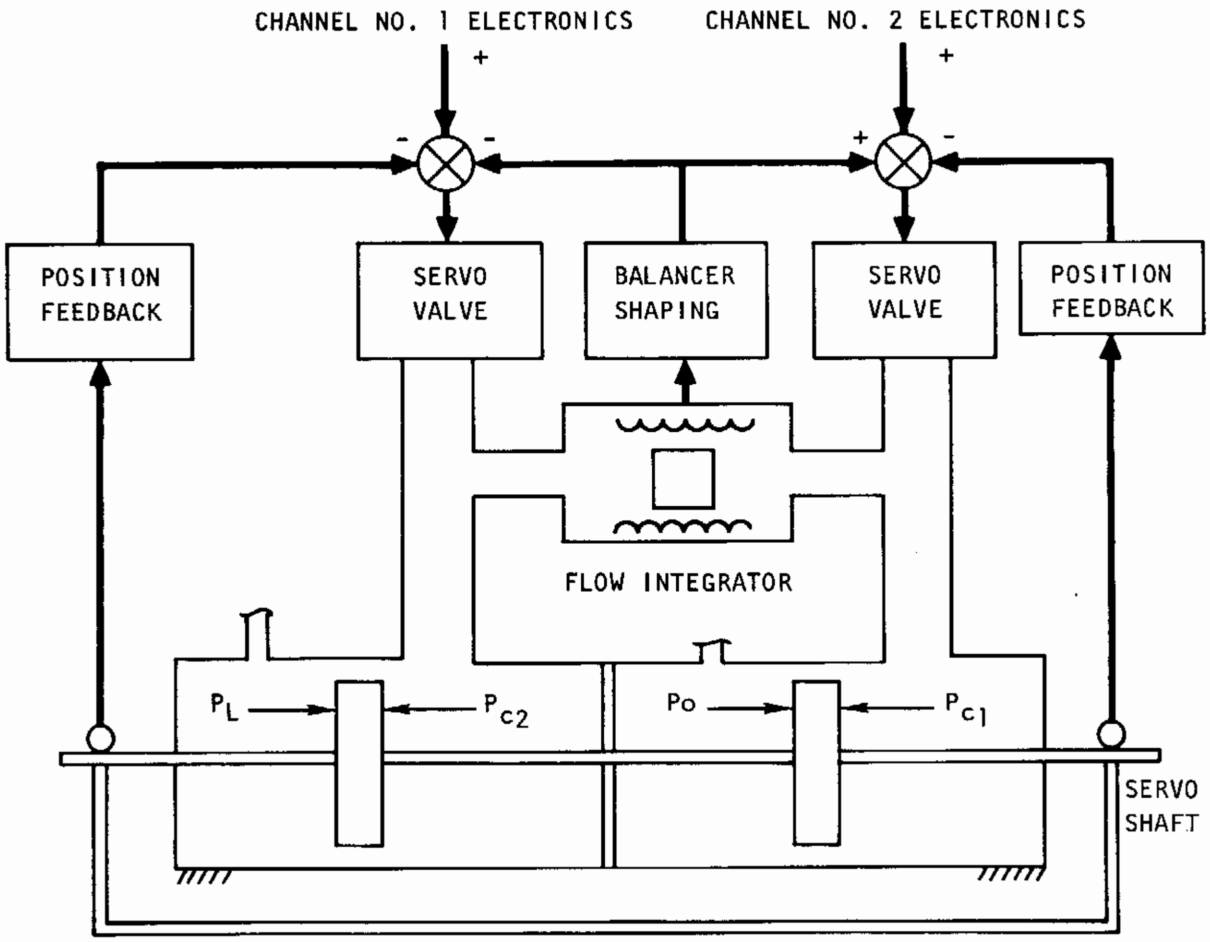
A functional block diagram of a single channel type system is shown in figure 7, along with estimated weights and failure rates. Adequate system performance can be obtained with a 25-percent servo authority limit. The stability augmenetation systems consists of single-channel electro-hydraulic servos, electronics, inertial sensors, and servo monitors. The monitors consist of dynamic shaping networks serving as servo models. The model outputs are compared to the actual servo displacement in response to the net input commands. The difference between the model and servo output is fed to a threshold network, and an excessive error between the signals will operate a hydraulic shutoff valve, and the servo will be recentered. The inertial sensors consist of rate gyros and accelerometers in the pitch and yaw axes, and a rate gyro in the roll axis. The estimated weight per axis is approximately 106 pounds for pitch and yaw, 51 pounds for roll, and about 80 pounds for dual tandem master cylinders in pitch and roll. The estimated failure rates are 4×10^{-4} per hour in pitch and yaw, and 1.8×10^{-4} per hour in roll, each in series with individual hydraulic system failure rates of about 3.65×10^{-4} per hour. The system would add about 237 pounds to the flight control system weight and the probability of the loss of an axis of augmentation during a 5-hour mission be about 0.82×10^{-2}. The system would be subject to undetected failures upstream of the monitored servo, and failures are about 1.25×10^{-4} per flight hour for pitch and yaw and about 4.25×10^{-5} per flight hour for roll. The probability of a potentially dangerous failure in a 5-hour mission would be about 8.38×10^{-4}, or about once every 6,000 flight hours. These failures would be hardovers of 25 percent control authority. A mechanization with a fail-soft capability is thus required. The loss of stability augmentation in the pitch or roll axis would revert the axis experiencing the loss to

Level 3 flying qualities because of the excessive sensitivities caused by the increased mechanical system gains and loss of feedback and damping. The probabilities of failure of the pitch or roll augmentation would be about 5.45 x 10^{-3} for a 5-hour mission. A more reliable mechanization with a fail-safe characteristic is required.

A triple redundant system consisting of three independent channels of sensors and electronics controlling three independently powered electrohydraulic force summed servos, or two active and a model, could be mechanized. This system would have a loss of function probability on the order of 0.6 x 10^{-4} for pitch and roll for a 5-hour mission. The failure probability is acceptable; however, the failure characteristics are still unacceptable. Protection against hardover failures is dependent upon the remaining active channels or channel to overpower and hold the failed channel. With three active channels, the first failure could be made acceptable, but protection against a second hardover failure would depend on matched hydraulic supply pressures. Normal operating hydraulic systems capable of doing their jobs could at any time be mismatched in pressure by over 25 percent. This would allow the failed channel to drive the system output at maximum rate until the failure was detected and the system could be depowered. Dependence on monitoring with rapid cutoff to limit control surface travel to acceptable magnitudes is self-defeating because of the lowered reliability caused by nuisance trip-outs of good systems due to normal system mismatches. A system mechanization based on velocity summed electromechanical motors could also be considered a candidate. This system would provide acceptable system failure rates, but again the system second failure characteristics would be unacceptable. Protection against a hardover second failure would be dependent on maximum velocity matching of the remaining "good" motor and the failed motor. This matching is difficult to control, and normal system and electrical supply tolerances could result in terminal velocity mismatches on the order of 30 percent or greater. This could result in control surface motion, due to a hardover failure, at least one-third maximum rate. Limiting displacement by rapid cutoff would result in the same problems as discussed for the hydraulic servo system.

To overcome the aforementioned problems, a dual-dual or two sets of dual tandem electrohydraulic servos is proposed. Each servo would be controlled by identical, but independent, channels of sensors and electronics. Each servo is powered by an independent hydraulic system, with the piston pair in the servo powered by the same hydraulic system. This insures that matched hydraulic pressures will be available to each piston pair to provide hardover failure protection.

Figure 8 presents a schematic of the dual tandem fail-safe servo concept. The systems are provided with differentail hydraulic flow transducers which provide an electrical signal proportioned to the difference in



INCREMENTAL SHAFT DISPLACEMENT DUE TO SIGNAL IN ONE CHANNEL ONLY CAUSES MAXIMUM OPPOSING FORCE IN OTHER CHANNEL BECAUSE OF HIGH GAIN POSITION FEEDBACK.

BALANCER EQUALIZES VALVE SIGNALS AT CONTROLLED RATE, RESULTING IN SAFE TRANSIENTS DUE TO ANY FAILURE.

P_c = VALVE CHAMBER PRESS

P_o = RETURN PRESS

P_L = LINE PRESS

Figure 8. Fail-Safe Servo Concept

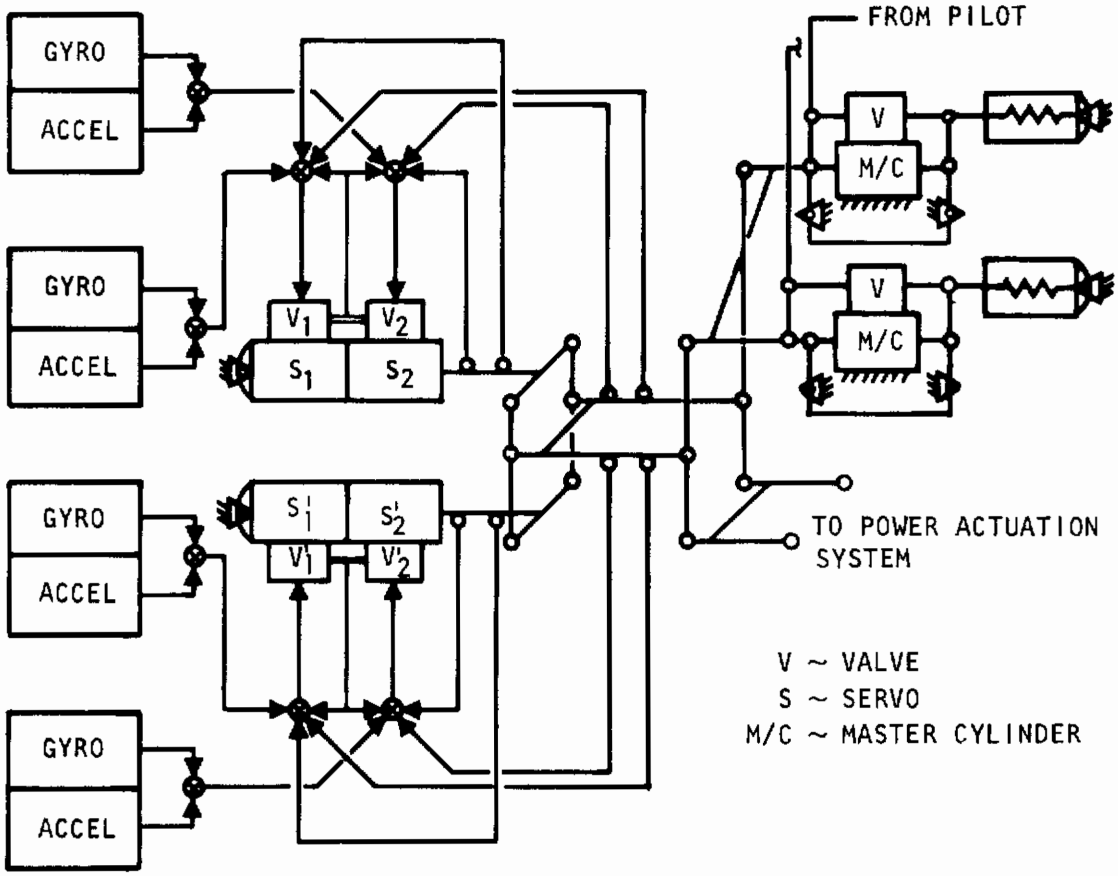
hydraulic flow from the two valves. This signal is dynamically shaped and fed back with opposite signs to the two systems for balancing. Should the balancer be unable to rebalance a system mismatch sufficient to bottom the differential transducer in about 3 seconds, dual series shutoff valves would be signaled to block hydraulic power, and the system would be recentered at a controlled rate. The system output motion resulting from the failure and balancer action could be controlled to an acceptable level. The dual channel system is functionaly a single system with controlled failure characteristics and double the single channel system failure rates. The two dual systems would be position summed, and the summed position would be fed back to the individual channels to hold the gain reduction to an acceptable level in the event of a single failure.

Figure 9 presents a schematic of the fail-operational, fail-safe configuration. The probability of the loss of pitch, roll, or yaw augmentation in a 5-hour mission would be about 7.3×10^{-5}. The system provides adequate flying qualities reliability, and has acceptable failure characteristics. The system would have neglible effect on the loss of control probability, which would remain at about 7.6×10^{-5} for a 5-hour mission. The system flight safety probabilities still do not match the requirements of 10^{-5} set forth as a goal for a transport in the 1970's. A more reliable mechanization must be found. The pitch, roll, and yaw augmentation system would weigh about 425 pounds plus about 80 pounds for two dual tandem master cylinders in both pitch and roll. This would total about 3,465 pounds per shipset.

MECHANICAL CONTROL PLUS CONTROL AUGMENTATION

The addition of the fail-operational, fail-safe stability augmentation to the basic dual mechanical control system resulted in a system which provides the capability of increasing system performance and decreasing system weight. The dual mechanical control system was required to decrease the loss of control failure probabilities at the expense of about 654 pounds of system weight. The gearing of this system was nonoptimum for operation without stability augmentation in the pitch and roll axis. If an electrical control path were to be added to the stability augmentation systems, the possibility exists of eliminating the duality requirements for the mechanical control paths and optimizing them for operation with stability augmentation failed. When placed in parallel with single mechanical control paths, the electrical control paths would provide control redundancy and could be optimized for operation with the mechanical control system and stability augmentation.

The changes to the stability augmentation system would be an increase in servo authority to 100 percent and the addition of quadruple position



RELIABILITY - 10^{-6}/HR

SERVO CYLINDER	2.5
VALVE	50.0
DRIVER	15.0
PICKOFF	7.5
FLOW INTEGRATOR	20.0
MISCELLANEOUS	20.0
	115.0

GYRO	35
ACCELERATOR	20
ELECTRICAL	70
SHUTOFF VALVE	35
BALANCER	20
MISCELLANEOUS	20
	200
	115
	315×10^{-6}/HR

$2(315)10^{-6} = 0.630\times10^{-3}$/HR - SERVO LOOPS

0.365×10^{-3}/HR - HYDRAULIC SYSTEM

0.995×10^{-3}/HR

$(0.995\times10^{-3}/\text{HR})^2 = 0.990\times10^{-6}/\text{HR}^2;\quad 25\times10^{-6}$ for 5 HR MISSION

ESTIMATED WEIGHT FOR THREE AXES OF SAS - 425 POUNDS
PITCH AND ROLL DUAL M/C - 80 POUNDS
TOTAL - 505 POUNDS

Figure 9. Dual SAS System Plus Interconnects

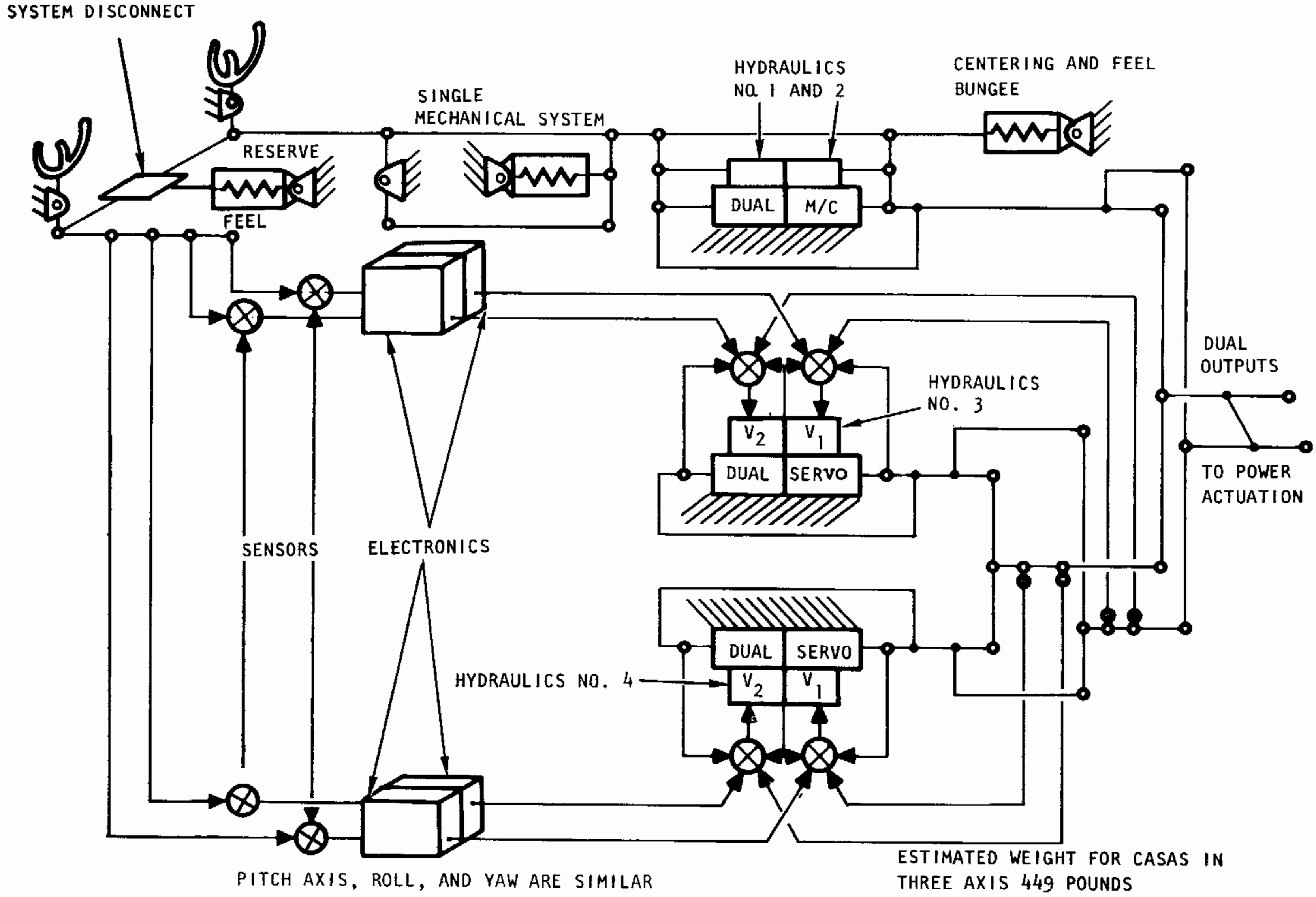
pickoffs to the pilot's controls. The position pickoffs would add about 24 pounds to the augmentation system weight and would eliminate about 654 pounds from the mechanical control system. Performance could also be improved by the added flexibility for matching control sensitivity and dynamics to air vehicle response. Improvement could also be realized in small amplitude control because of better resolution characteristics of the electrically controlled servos.

Figure 10 presents a simplified schematic of the pitch axis, less the DLC, utilizing this mechanization.

For loss of control considerations, the mechanical system disconnect probabilities are in parallel with the electrical control and stability augmentation system failure probabilities. As before, these failure probabilities estimates excluded the yaw axis, roll ailerons or spoilers, and pitch DLC except for jams. All jam probabilities are added in series with the foregoing parallel estimates. For a 5-hour mission, the single mechanical control system disconnect probability was about 2.34×10^{-4}, and the fail-operational electrical control system failure probability would be about 1.6×10^{-5}. This would result in a loss of control, for nonjammed reasons, of about 0.004×10^{-6}. The probability of loss of control because of a system jam, including master cylinder and servo summing linkages would be about 4.3×10^{-5} for a 5-hour mission. The system weights are summarized as follows:

Power actuation system and cockpit controls	1,652 lb
Single mechanical control system	654
Control and stability augmentation system	449
Pitch and roll master cylinders	80
Controls disconnect	20
Total system weight	2,855 lb

The inclusion of a mechanical system disconnect which could disconnect the mechanical system in the event of a jam upstream of the summing point of the master cylinders and SCAS servos would relieve this situation to some degree. This disconnect would connect in a new feel bungee and disconnect the jammed mechanical system. It would also increase the column and wheel to surface gains to compensate for the loss of the mechanical system. Normal flight could be continued by the pilot with Level 1 flying qualities. Those components beyond the summing linkage would be dualed, easing the disconnect problem, but doubling the jam rates to the input of the power



PITCH AXIS, ROLL, AND YAW ARE SIMILAR

ESTIMATED WEIGHT FOR CASAS IN THREE AXIS 449 POUNDS

Figure 10. Dual CASAS Plus Mechanical System

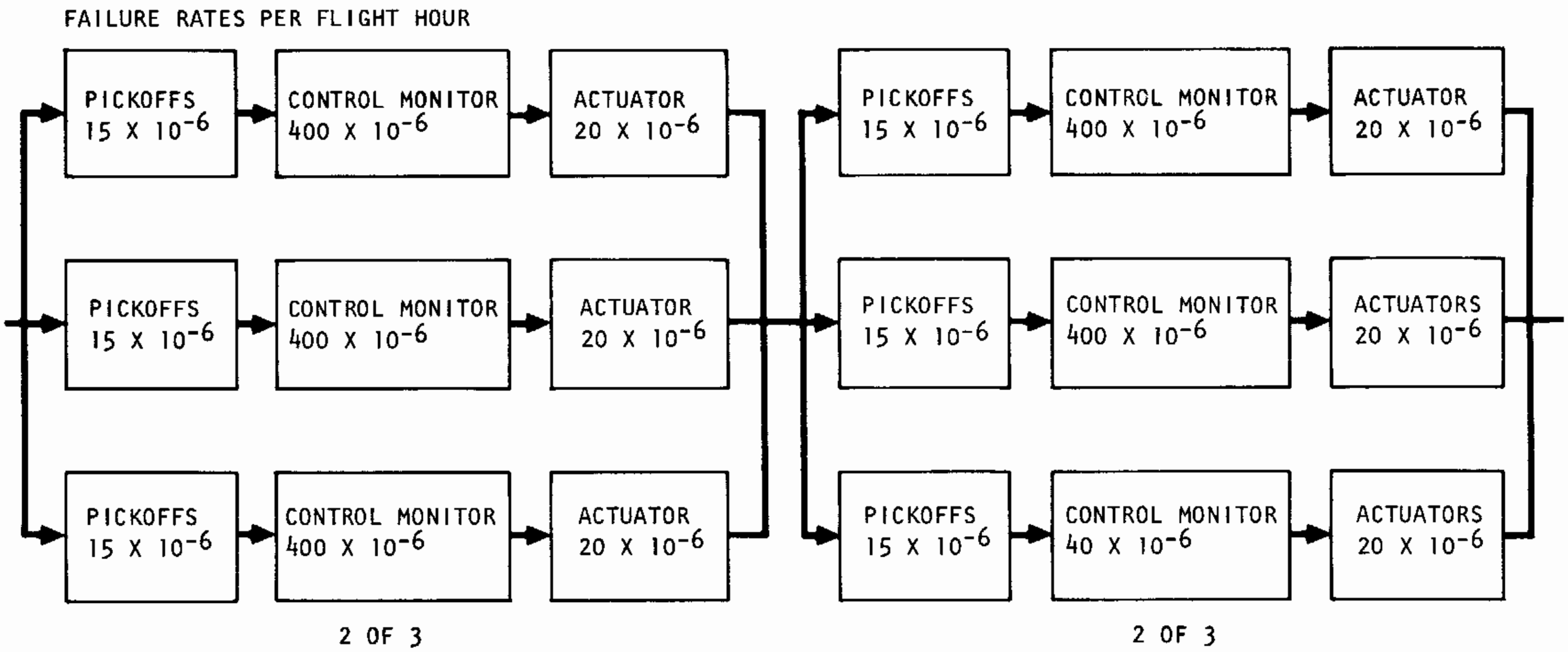
actuation system. This would include the controls to the spoiler and ailerons in the wings and the flap gearing in the pitch system. This would mean a jam rate of 2.6 x 10^{-6} per hour for roll, and 0.25 x 10^{-6} for pitch for a total of 2.85 x 10^{-6} per hour plus that of the power actuations system, about 2.7 x 10^{-6} per hour, and about one-half of the disconnect and jam rates of the control column and wheel, about 0.06 x 10^{-6} per hour. This would amount to a net total of about 5.11 x 10^{-6} per hour. this would result in a loss of control probability of about 2.5 x 10^{-5}, based on a 5-hour mission. This exceeds the flight safety goal of 10^{-5} by a good margin; however, the development risk of this type of system would be low. The CASAS, with the disconnectable mechanical system is essentially the same as that being developed for the B-1. The CASAS has been flight test proven on the F-100, F-107, and the XB-70, as well as many hours of flight simulation effort.

FLY-BY-WIRE CONTROL WITH MECHANICAL REVERSION

A flight control system based on fly-by-wire with a mechanical control system for backup is considered as a trade candidate. This system would feature a single mechanical control system in each axis, as previously described. These systems are less the dual tandem hydraulic master cylinders, and have mechanical gearing changers located at the pilot's stations. These gearing changes normally have the mechanical system disengaged from the cockpit controls, and control is maintained through the control and stability augmentation system. The outputs of the mechanical system are directly summed with the outputs of the electrohydraulic servos. The master cylinders are not required, since the system is disengaged under normal conditions.

The pitch axis DLC is electrically driven by a fail-operational, fail-closed electrical motor velocity summed system. Figure 11 presents a simplified failure probabilities schematic of this system. There is one of this type of system in each wing. In the event of a second failure in either of the two systems, both are shut down, and the power actuator controls are bungee driven to the closed positions. The system has a failure probability of about 2.8 x 10^{-5} per hour for a 5-hour mission. Level 2 flying qualities is retained after a system failure.

The control and stability augmentation system operates to maintain trim and give the pilots full control over the operational range of the air vehicle. The servo action is essentially the same as described in the preceding section, except that they are hooked up differently. They are fail-operational twice; that is, it would take three failures to cause the system to refuse control. Four actuation systems would be assigned to roll, one at each aileron, and one at each of the spoiler inputs, two for



$2 \times 3\ (4.35 \times 10^{-4}/\mathrm{HR})^2 = 6\ (18.9)\ 10^{-8}/\mathrm{HR}^2 = 1.13 \times 10^{-6}/\mathrm{HR}^2$

28.25×10^{-6} FOR A 5-HOUR MISSION = P_F

Figure 11. Triple Redundant Spoiler System Failure Probabilities

pitch and one for yaw. Two systems will be considered, four active servos force summed, and four limited position summed single systems.

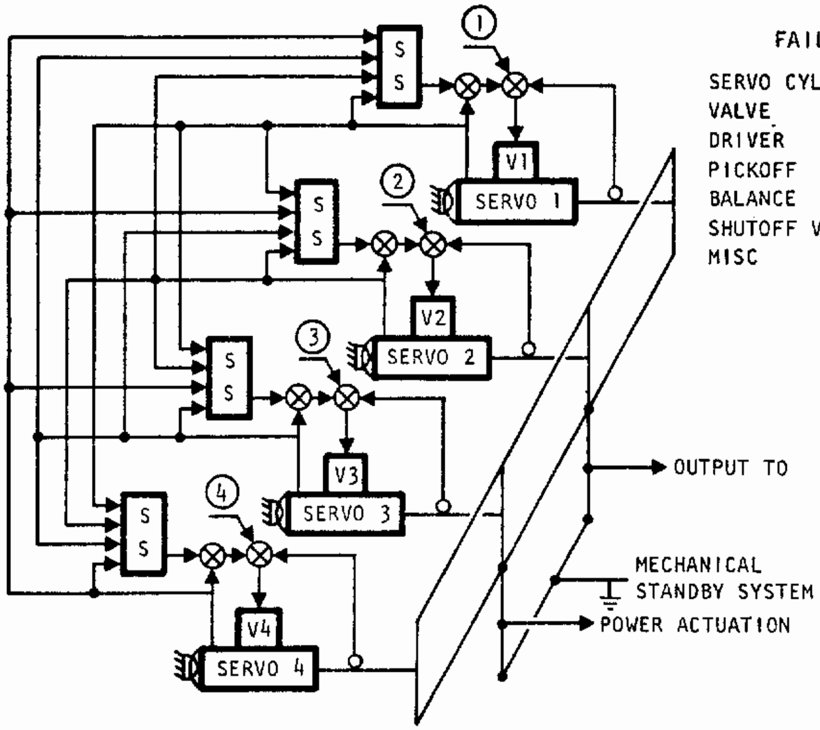
Figure 12 presents a simplified schematic diagram of the difference between the two systems. The outputs of the mechanical backup system are summed with this system, but normally are zero. Each system is provided with an independent electrical and hydraulic power supply.

The first system to be examined is the force summed system. Figure 13 presents a schematic of this system. This system contains four servos with the outputs tied together. These servos are force summed at the outputs, and, as such, they will require pressure balancing to bring the pressures into the range where there will be acceptable operation. A median signal selector is used to pick off a median differential pressure, and this pressure is compared to the individual servo differential pressures. The error between the differential pressures is shaped and fed back to the values in a sense to neutralize them. The differential pressure is picked off by differential pressure transducers across each piston. If a signal is fed to one servo, and the balancer cannot neutralize the resultant pressure differential within a specified time, that servo is shut down and bypassed. After two failures, the system remains in operation until a third failure causes it to become uncontrolled. After the third failure, the system is shut down and recentered by bungee action. The pilot then uses his emergency backup mechanical system to maintain control of the aircraft, and land it. The first and second failures will be acceptable because they will have at least two good servos to buck out the failed servo. The control surface transients resulting from these failures are a function of the rates assigned to the pressure balancer and, as such, are directly controlled by the system designer.

As a result of this short analysis, it can be seen that this system is acceptable from an operational point of view. It remains now to analyze its failure probabilities. Figure 14 presents a simplified reliability diagram of the system. To start with, the cockpit control and surface actuator systems have a failure rate of about 3.2×10^{-6} for a 5-hour mission. What remains lies in between these two elements. If the system lying in between can be found to have a failure rate of less than 6.8×10^{-6} for the 5-hour mission, all of the systems requirements will be met. With reference to figure 14, it can be seen that the systems have a net failure rate of about 2.6×10^{-6}. This summed with the output stages, control column, and wheel and hydraulic systems will result in about 5.8×10^{-6} for the overall system. The reversion to the mechanical system would have a probability of occurrance of about 2.55×10^{-6}. The failure analysis is applicable to both systems.

The second system to be looked at consists of four servos, the outputs of which are position summed. This alleviates the need for pressure

PRESSURE SUMMED SYSTEM



FAILURE RATES X 10^{-6}/HR

SERVO CYL	2.5	GYRO	35
VALVE	50	ACCEL	20
DRIVER	15	GAIN	50
PICKOFF	7.5	ELECT.	100
BALANCE	80	MISC	45
SHUTOFF VALVES	70		250
MISC	25		
	250.0		

POSITION SUMMED SYSTEM

FAILURE RATES X 10^{-6}/HR

SERVO CYL	2.5	GYRO	35
VALVE	50.	ACCEL	20
DRIVER	15.	GAIN	50
PICKOFF	15.	ELECT.	100
SHUTOFF VALVES	70.	MISC	45
MISC	50.		250
	202.5		

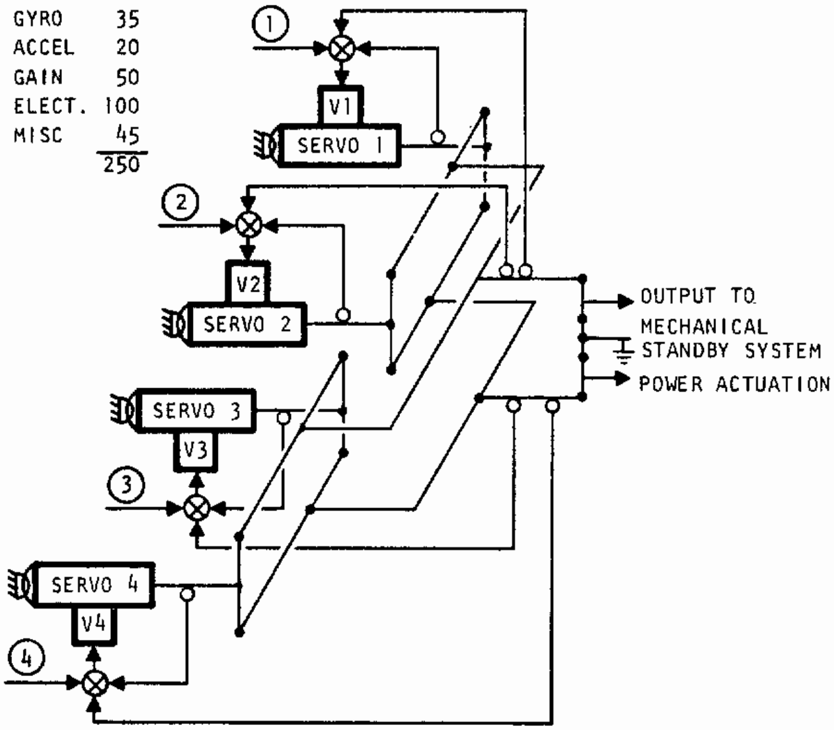
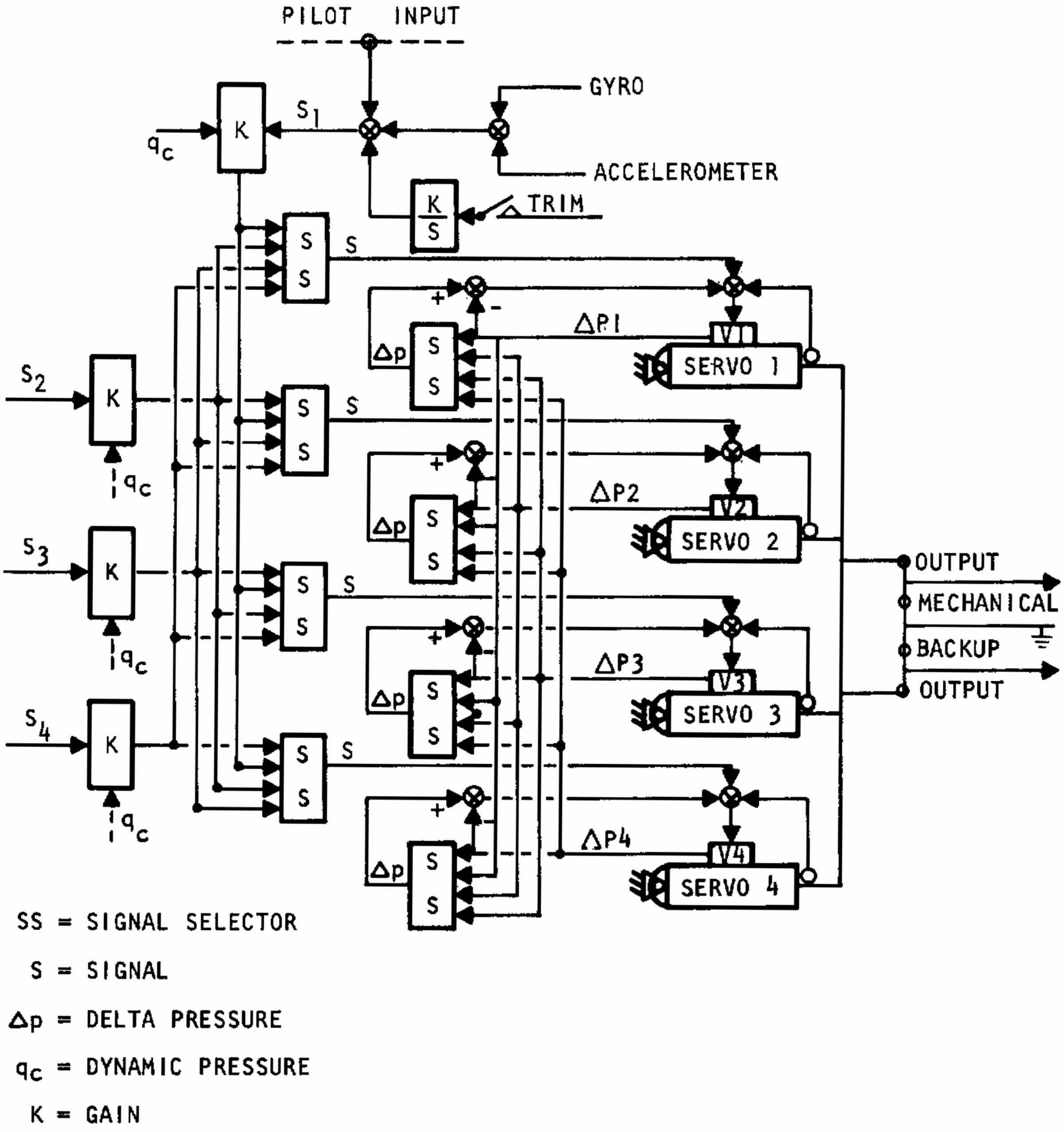


Figure 12. Fly-by-Wire Servo Systems



SS = SIGNAL SELECTOR

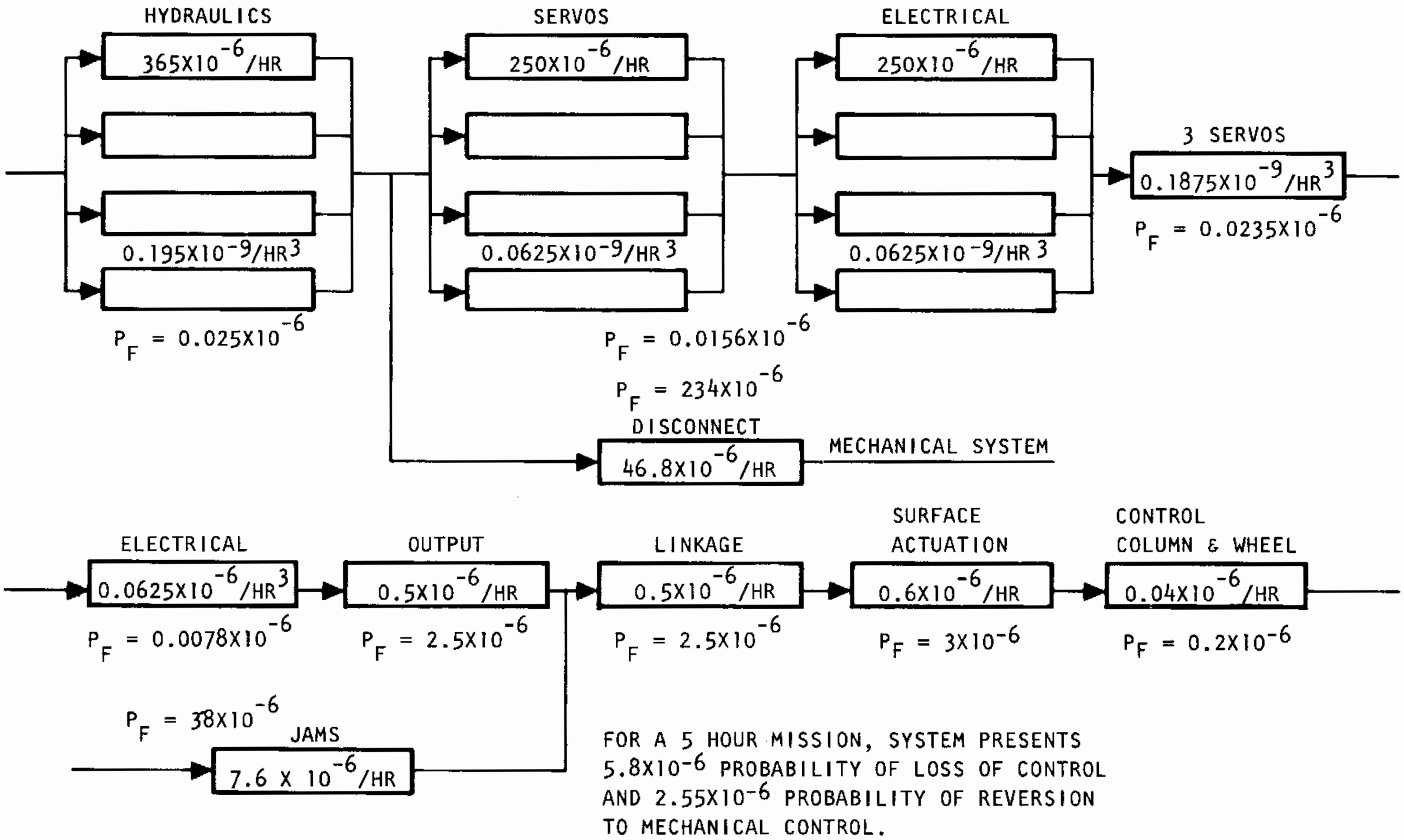
S = SIGNAL

Δp = DELTA PRESSURE

q_c = DYNAMIC PRESSURE

K = GAIN

Figure 13. Quadruple Fly-by-Wire System



FOR A 5 HOUR MISSION, SYSTEM PRESENTS $5.8X10^{-6}$ PROBABILITY OF LOSS OF CONTROL AND $2.55X10^{-6}$ PROBABILITY OF REVERSION TO MECHANICAL CONTROL.

Figure 14. Fly-by-Wire Plus Mechanical Backup Failure Probabilities

balancing the servos to obtain normal working conditions. The servos are summed on walking beams, and are restricted in travel to 50 percent of the rated output. This gives the servo set 200 percent authority with all servos working, and 100 percent authority with two failures. There are override bungees placed in the summed linkages to absorb over travel. Feedback is provided around each servo, and from the summed output. A hardover signal into one of the servos would cause it to go hardover. The feedbacks in the other channels would act to overcome the output motion due to the failed servo. After some time delay, the voted bad servo would be cut off and recentered. the second failure would be much the same as the first, except that there would be only two servos left to overcome the failed servo. The first failure will be opposed by three working systems, and the second failure will be opposed by two working systems. The input to the control surface due to a failure is a function of the preceding failure, the gain of the feedback from the summing linkage, the authority of each servo, and the gain of the feedbacks assigned to the inertial feedback sensors. The first failure could drive the summing linkage, with the three remaining servos opposing the uncommanded motion. If the summed output feedbacks are made five to one for the individual servo feedbacks and the response feedback were made one, then the response to a first failure would be about 0.05 g. This is acceptable, and the second failure would result in about 0.07 g. This is acceptable. The actual feedback ratio used would depend on the vehicle gains however, these numbers are representative of the aircraft under consideration.

The failure rate of this system will be about the same as the preceding force summed system. With both systems having about the same order of magnitude of failure rates, and the same order of recovery, then special thought must be given to choosing between the two. The pressure balanced system is much like the present B-1 system. The pressure balancer replaces the flow integrator, and the inputs are selected, however, the basic system is similar to the B-1 system. The position system is similar only in that the outputs are position summed, however, the basic system is different. In order to be able to predict the resultant g's that follow a hardover failure, the aircraft's flight characteristics must be predicted very closely, and the systems aerodynamic gains must be made precisely. The pressure summed system would give the system designer a much closer control of this function, with less dependence upon the aerodynamic gains. The mechanical backup system removes the doubt that goes with a fly-by-wire system, and the pressure balanced system is chosen as the candidate. The following presents a weight breakdown of the system:

Power actuation system and cockpit controls	1,652 lb
Control and stability augmentation system	609

Single mechanical control system	654
Controls disconnect	20
Total system weight	2,935 lb

FLY-BY-WIRE CONTROL

The flight control system could be made lighter if the mechanical backup control system could be removed. This could be done if the probability of reversion to the mechanical control system were below 6 x 10^{-6} for a 5-hour mission. Based strictly on the failure rate data that are available for use today, this is possible. In the preceding paragraphs, it was seen that the control surface system including the mechanical system had a failure probability on the order of 5.8 x 10^{-6} for a 5-hour mission, and that the fly-by-wire system with the mechanical backup system disconnected had a failure probability of about 2.55 x 10^{-6}. This means that removal of the mechanical backup system would increase the failure rate by 2.55 x 10^{-6} for a total of about 8.35 x 10^{-6} for a 5-hour mission. The increase in failure allotment appears to be reasonable if the electrical failure rates can be sustained.

The electrical failure rates appear realistic on the surface; however, they do not account for such phenomena as a complete electrical system failure. Such a complete electrical system failure might be very rare in the life time of the air vehicle. However, even something as rare as this may become tactically unacceptable when it results in the loss of the aircraft. Such failure may result from lighting strikes on the air vehicle, best known of the phenomena which cause breakdown of aircraft electrical systems. This consideration is particularly important if the vehicle is an all-weather aircraft. No attempt will be made at this time to trace out the exact course of the happenings that cause the loss of electrical power. Sufficient to say at this point that such electrical problems have existed in the past and regardless of the causes, these problems still represent a significant risk. In addition to the electrical system problems, there are the problems of environment, neutron, and electromagnetic interference, and development risk. The problem of development risk should not be bypassed lightly. It is this risk which must be considered when entering flight test with no backup system to save the air vehicle in case of designer's calculation are wrong.

This system would be essentially like the fly-by-wire system with the standby mechanical system. The dual outputs would be fed directly to the dual inputs of the power actuation system. Level 1 flying qualities would be provided in all flight regimes with a probability of loss of 8.89 x 10^{-6}

for a 5-hour mission. The probability of loss of control would be 8.35 x 10^{-6}. The systems weights would be the fly-by-wire with mechanical backup less the mechanical system. The systems weights are as follows:

Power actuation system plus cockpit control	1,652 lb
Control and stability augmentation	609
Total weight	2,261 lb

AUTOMATIC FLIGHT CONTROL

The addition of an automatic flight control system to the basic control system is quite straightforward. This system provides considerable pilot duty relief, at a cost of approximately 50 pounds of installed weight. This control system consists of the central air data system, the platform, a coupler, and the stability augmentation system. It functions to maintain the flight path of the aircraft under constant surveillance and control when engaged. The system would provide roll angle hold in the roll axis, and the flight path or altitude hold in the pitch axis. When the control column or wheel is moved away from neutral, the system synchronizes the incoming signal. This is done to insure that the values existing at the time that the cockpit controls are placed back in neutral will be held. These values are wings level or beyond say ±2.5 degrees to ±45 degrees the attitude existing at the time of centering the controls. In pitch, the value held would be altitude if below a given flight path angle and flight path angle if above say ±1 degree. Other modes of operation are available by special selection. These modes are airspeed or mach number hold, automatic navigation, automatic landing, and whatever other modes may make themselves known as the aircraft is developed.

The system is dualed all the way from the sensors to the input to the augmentation servos. The reason for this is really self-explanatory in concept. A single system can put in a larger input that can be tolerated during a hardover failure. The two systems are monitored, and a difference between them causes a system shutdown when this difference exists over a time span of say 1/2 to 1 second, and is of a fairly large magnitude. The system is nonswapping, that is it does not switch from one signal to another during operation. It remains with the same signal until it is shutdown. Shutdown would have a probability of about 10^{-3} in a 5-hour mission. This is comparable to about 20 failures every 20,000 5-hour missions. This is considered to be adequate mission reliability.

This automatic flight control capability could be added to any of the systems previously discussed, but does not provide an alternate method with the same functional capability provided by those systems. Consequently, it has not been included in the mechanization comparisons discussed in later sections.

SECTION III

SYSTEM CHARACTERISTICS COMPARISON

A summary of all of the control systems studied is presented in table I. This table starts at the top with the mechanical system and works down to fly-by-wire at the bottom. This table summarizes the systems versus the system requirements, as presented in section II. In this table, it can be seen that the nechanical control system meets only requirements 2, 4, and 8 of the basic requirements, while missing requirements 1, 3, 5, 6, and 7. The systems composed of the mechanical system plus SAS and mechanical plus CASAS meet all system requirements, except for loss of control, requirement 5. The systems composed of fly-by-wire with dormant mechanical system backup and the fly-by-wire system meet all system requirements. The requirement represented by number 5 says simply that the combination of any failures causing an unsafe flight condition to exist shall have a probability of occurrence less than 10^{-5} for a 5-hour mission.

The fly-by-wire systems are the only systems that meet this requirement. This is primarily due to the placement of servos at the power actuators and the removal of the mechanical system jam rates that occur between centrally located servos and the power actuation system. Table II presents a summary of all of the systems weights. This table includes the weights of single and dual mechanical systems, single and dual SAS, the basic power actuation and cockpit control systems, and the weights of the fly-by-wire systems. This table was included to provide the background for the weight summary presented in table III. Table III also presents the probabilities of loss of control and loss of Level 1 flying qualities for each of the systems under consideration. Table III sets the basic background for the selection of the control system recommended for the MST.

Table IV presents a more detailed summary of the systems without regard to the system requirements. In this table, the cost of added system weight; the cost of the probability of loss of control; the cost of the probability of loss of Level 1 flying qualities; procurement, development, design and analysis, and maintenance costs; and the cost of risk of development are presented. For each of the systems, these relative costs were developed from the following set of generalized equations:

1. Cost of added weight:

   This section considers only the cost of a larger aircraft plus the added cost of operating the larger aircraft.

TABLE I. CONTROL SYSTEM VERSUS REQUIREMENTS

Control System	Requirement Number *							
	1	2	3	4	5	6	7	8
Mechanical	O**	M***	O	M	O	O	O	M
Mechanical plus SAS	M	M	M	M	O	M	M	M
Mechanical plus CASAS	M	M	M	M	O	M	M	M
Fly-by-wire plus mechanical backup	M	M	M	M	M	M	M	M
Fly-by-wire	M	M	M	M	M	M	M	M

NOTES

* Requirement number refers to requirements listed in "Ground Rules," section II.
** O = does not meet
*** M = does meet

TABLE II. CONTROL SYSTEM WEIGHTS (POUNDS)

① BASIC POWER ACTUATION AND COCKPIT CONTROLS		
Horizontal Stabilizer	3 act. and valves and linkage	204
Elevator	3 act. and valves and linkage	152
Rudder	3 act. and valves and linkage	152
Ailerons	6 act. and valves and linkage	328
Roll spoilers	6 act. and valves and linkage	328
DLC spoilers	6 act. and valves and linkage	328
Cockpit controls	(2 sets)	160
Total		1,652
② MECHANICAL CONTROLS, FEEL, LINKAGE, TRIM (SINGLE SYSTEM)		
Cable system		408
DLC		57
Trim and feel		135
Flap functions		54
Total		654
③ MECHANICAL CONTROL SYSTEM		
① + 2 ② = basic and dual mech		2,960

(4a) MECHANICAL AND STABILIZER AUGMENTATION (SINGLE AUG, AXIS)	
Servo	15
Electrical	20
Gyro	3
Acceleration	3
Miscellaneous	12
Total	63
Pitch and yaw	160
Roll	51
Master cylinders	80
Basic and dual mech =③	2,960
Total	3,197
(4b) MECHANICAL AND SAS (DUAL SAS AND DUAL MECH)	
Pitch and yaw (dual)	212
Roll (dual)	102
Balancing and Monitoring	111
Master cylinders	80
Basic and dual mech =③	2,960
Total	3,465

⑤ MECHANICAL AND CASAS (CASAS AND SINGLE MECH)	
Pitch, roll, yaw, (dual); from 4b	425
Position pickoffs	24
Master cylinders	80
Basic and single mech; ① and ②	2,306
Disconnect	20
Total	2,855

⑥ FBW WITH MECH REVERSION	
Pitch, roll, yaw (4-channel) aug	499
Disconnects	40
Basic and single mech	2,306
BITE	60
Added servos	100
Total	2,955

⑦ FBW	
Pitch, roll, yaw (4-channel) aug	449
Basic	1,652
BITE	60
Added servos	100
Total	2,261

TABLE III. CONTROL SYSTEMS - FAILURE PROBABILITIES AND WEIGHTS

SYSTEM	Loss of Level 1	Loss of Control	Weight (lb)
Mechanical*	1	7.6×10^{-5}	2,960
Mechanical plus SAS	1.49×10^{-4}	7.6×10^{-5}	3,465
Mechanical plus CASAS	4.16×10^{-5}	2.56×10^{-5}	2,855
Fly-by-wire with mechanical backup	8.89×10^{-6}	5.8×10^{-6}	2,955
Fly-by-wire	8.89×10^{-6}	8.35×10^{-6}	2,261

*Level 1 flying qualities are not provided

TABLE IV. SYSTEMS COSTS (IN $ x 10^6)

SYSTEM	ADDED WEIGHT	PROB OF LOSS OF CONTROL	PROB OF LOSS OF LEVEL 1	RISK	COST	TOTAL
MECHANICAL SYSTEM	0.346	1.06	*	0.053	3.81	*
MECHANICAL SYSTEM PLUS SAS	0.589	1.06	0.061	0.1185	6.44	8.269
MECHANICAL SYSTEM PLUS CASAS	0.284	0.356	0.017	0.1185	6.42	7.196
FLY-BY-WIRE WITH MECHANICAL BACKUP	0.343	0.081	0.0035	0.170	7.663	8.260
FLY-BY-WIRE	0	0.1162	0.0035	0.530	8.935	9.585

*Does not provide mission completion capabilities

$$\Delta \text{ cost of added wt} = \frac{\text{dollars}}{\text{pounds a/c}} \text{ X } \Delta \text{wt X growth factor}$$

$$+ \ \Delta \text{ operating cost}$$

Where each of the preceding factors were assigned the following values:

$$\frac{\text{dollars}}{\text{pounds a/c}} = \frac{\$7 \text{ X } 10^{+6}}{0.103 \text{ X } 10^{+6} \text{ pounds}} = \$68/\text{pound}$$

ΔWt = weight of system under consideration - weight of

fly-by-wire system; growth factor = 3 pounds/pounds;

$$\Delta \text{ operating cost} = \frac{\text{dir op cost}}{\text{mission}} \text{ X } \frac{\text{No. of missions}}{\text{a/c life}}$$

$$\frac{\Delta \text{wt X growth factor}}{103 \text{ X } 10^{+6} \text{ pounds}}; \quad \text{where } \frac{\text{dir op cost}}{\text{mission}} = \frac{\$5{,}000}{\text{mission}}$$

$$\text{and } \frac{\text{missions}}{\text{a/c life}} = 2 \text{ X } 10^{3}$$

The direct operating costs were based on the costs of operating a C-141, and include fuel, expendables, direct maintenance, crew upkeep, and replaceable spares, with allowance for different operating conditions. The delta weight times growth factor over nominal weight was determined as follows:

Mech. system $\dfrac{(2{,}960 - 2{,}261) \text{ lb X } 3}{0.103 \text{ X } 10^{+6} \text{ lb}} = 0.021$

Mech. plus SAS $\dfrac{(3{,}465 - 2{,}261) \text{ lb X } 3}{0.103 \text{ X } 10^{+6} \text{ lb}} = 0.035$

Mech. plus CASAS $\dfrac{(2{,}855 - 2{,}261) \text{ lb X } 3}{0.103 \text{ X } 10^{+6} \text{ lb}} = 0.017$

Fly-by-wire plus mech backup $\dfrac{(2{,}955 - 2{,}261) \text{ lb X } 3}{0.103 \text{ X } 10^{+6} \text{ lb}} = 0.0202$

2. Cost of probability of loss of control:

$$\text{Cost } P_{f}\text{Lc} = \frac{\text{dollars}}{\text{a/c}} \text{ X } \frac{\text{probability of loss of control}}{\text{mission}} \text{ X } \frac{\text{missions}}{\text{a/c life}}$$

$$\text{where } \frac{\text{dollars}}{\text{a/c}} = \$7 \text{ X } 10^{6}$$

3. Cost of probability of loss of Level 1 flying qualities:

$$\text{Cost } P_f L1 = \frac{\text{dollars}}{\text{mission}} \text{ X } \frac{\text{probability of mission abort}}{\text{mission}} \text{ X } \frac{\text{missions}}{\text{a/c life}}$$

$$\frac{\text{Probability of mission abort}}{\text{mission}} = \frac{\text{probability of loss of level 1}}{\text{mission}}$$

$$\frac{\text{Dollars}}{\text{Mission}} = \frac{\text{operating cost}}{\text{mission}} + \frac{\text{maintenance cost}}{\text{mission}} + \frac{\text{cargo cost}}{\text{mission}}$$

$$\frac{\text{Operating cost}}{\text{Mission}} = \$5{,}000$$

$$\frac{\text{Maintenance cost}}{\text{Mission}} = \frac{\text{maintenance hr}}{\text{mission}} \text{ X } \frac{\text{dollars}}{\text{maint hr}} = 100 \text{ X } 600 = \$60{,}000$$

$$\frac{\text{Cargo cost}}{\text{Mission}} = \frac{\text{dollars}}{\text{lb}} \text{ X lb cargo} = 5 \text{ X } 28{,}000 = \$140{,}000$$

$$\frac{\text{Dollars}}{\text{Mission}} = 5{,}000 + 60{,}000 + 140{,}000 = \frac{\$0.205 \text{ X } 10^6}{\text{mission}}$$

4. Cost of procurement development, design and analysis, and maintenance:

Cost = procurement + maintenance cost

The augmentation system, consisting of mechanical plus SAS and CASAS and fly-by-wire with mechanical backup, will require about twice as much analysis, design effort, and testing as the purely mechanical system, and will cost at least twice as much to procure. The mechanical plus SAS must be given a slightly higher cost factor than the mechanical plus CASAS or the fly-by-wire with mechanical backup, because of the loss of flexibility in the design and the resultant need for more analysis effort. The fly-by-wire with mechanical backup will cost about 10 percent more than the mechanical plus CASAS, because of the additional design and analysis. The fly-by-wire alone system must be given a cost factor of about 1.25 times that of the mechanical plus CASAS or fly-by-wire with mechanical backup, because of the increased analysis, design, procurement, testing, and maintenance costs associated with the required additional builtin test requirements. A factor of 3 percent of the procurement costs of the airframe was used as the cost of the mechanical system.

With the aforementioned in mind, the following were set up as the procurement costs per system:

Mech system: Cost = $0.03 \times \$7 \times 10^6 = \$0.21 \times 10^6$

Mech system + SAS: Cost = $\$0.21 \times 10^6 \times 2 \times 1.05 = \$0.44 \times 10^6$

Mech system + CASAS: Cost = $\$0.21 \times 10^6 \times 2 = \$0.42 \times 10^6$

Fly-by-wire with mech system backup: Cost = $\$0.21 \times 10^6 \times 2 \times 1.1 = \$0.463 \times 10^6$

Fly-by-wire: Cost = $\$0.21 \times 10^6 \times 2 \times 1.25 = \$0.535 \times 10^6$

The system maintenance costs were set up as follows:

$$\text{Maint cost} = \frac{\text{dollars}}{\text{maint hr}} \times \frac{\text{flt cont maint hr}}{\text{mission}} \times \frac{\text{missions}}{\text{a/c life}}$$

$$\text{Where } \frac{\text{flt maint hr}}{\text{mission}} =$$

3 mech system
5 mech system plus SAS or CASAS
6 fly-by-wire plus mech backup
7 fly-by-wire

$$\text{and } \frac{\text{dollars}}{\text{maint hrs}} = \$600/\text{hr}$$

5. Cost of risk:

The cost of risk of development computed as follows:

$$\text{Cost of risk} = \frac{\text{dollars}}{\text{a/c}} \times \frac{\text{prob of unpred unsafe failure during}}{\text{prob of unpred unsafe failure during}}$$

$$\frac{\text{sys devmt}}{\text{mech sys devmt}} \times \frac{\text{prob of failure of immature system}}{\text{prob of failure of mature system}} \times$$

$$\frac{\text{prob of A/C loss with mech sys}}{\text{mission}} \times \frac{\text{missions}}{\text{A/C life}} = \$7 \times 10^{-6} \times KR \times 2 \times 76 \times 10^{6}$$

No. of devmt missions = \$1,060 X Kr X No. of devmt missions; where

\$1,060 X Kr X No. of mission = total

Mech $\$1,060 \times 1.0 \times 50 = \$0.053 \quad 10^6$

Mech + SAS $\$1,060 \times 1.5 \times 75 = \$0.1185 \times 10^6$

Mech + CASAS $\$1,060 \times 1.5 \times 75 = \$0.1185 \times 10^6$

Fly-by-wire with mech backup	$\$1,060 \times 1.6 \times 100 = \$0.170 \times 10^{6}$
Fly-by-wire	$\$1,060 \times 5.0 \times 100 = \$0.530 \times 10^{6}$

To use the preceding relationships, the cost of each of the systems was calculated and entered into table IV. The following is a sample of these calculations as made for the fly-by-wire with dormant mechanical backup.

1. Cost of added weight:

   $\$ \text{ added weight} = \$68\ (2,955 - 2,261)\ 3 + \$5,000 \times 2 \times 10^{3}$

   $\times \dfrac{694 \times 3}{0.103 \times 10^{6}} = \$6.141 \times 10^{6} + \$\ 0.202 \times 10^{6} = \$0.343 \times 10^{6}$

2. Cost of probability of loss of control:

   $\$P_{f}LC = \$7 \times 10^{6} \times 5.8 \times 10^{-6} \times 2 \times 10^{3} = \$0.08 \times 10^{6}$

3. Cost of probability of loss of Level 1 flying qualities:

   $\$P_{f}L1 = \$0.205 \times 10^{6} \times 8.89 \times 10^{-6} \times 2 \times 10^{3} = \$0.0035 \times 10^{6}$

4. Cost of procurement, development, design and analysis, and maintenance:

   $\$P\ \&\ M = \$0.463 \times 10^{6} + \$600 \times 6 \times 2 \times 10^{3} = (\$0.463 + \$7.2)\ 10^{6}$

   $= \$7.663 \times 10^{6}$

5. Cost of risk of development:

   $\$ \text{ risk} = \$7 \times 10^{6} \times 1.6 \times 2 \times 76 \times 10^{-6} \times 100 = \$0.170 \times 10^{6}$

   $\text{Total} = (\$0.343 + \$0.081 + \$0.0035 + \$7.663 + \$0.17)\ 10^{6} = \$8.260$

   $\times 10^{6}$

These values were entered into table IV, along with the systems total costs.

Examination of table IV will show that the procurement plus maintenance cost outweighs all other costs. There are several causes for this. In the cost of loss of control, only the cost of the lost aircraft is considered. This does not consider that cost of the probable loss of a combat trained crew, or their replacements. In the mission abort calculations, only a nominal fixed cost was assigned to the cargo. This does not account for the rapid escalation of the value of a military cargo delivered to the front when it is needed. The cost of the risk of development considers only the calculated system failure rates and their escalated values during system development. There are still the risks of unpredicted or unpredictable problems. These problems could be improper system or component failure rates, environmental conditions not as predicted with possible multiple or nonrandom failures occurring, and unforeseen failure modes. These problems are primarily of concern for the fly-by-wire system, since it alone has no mechanical backup system to assure that the crew will have a means of getting home, should a control axis go out of control. With these considerations in mind, the fly-by-wire and the fly-by-wire with mechanical backup systems were chosen as the two candidates. The two systems are very close in net costs to the Air Force, with the fly-by-wire at about $\$9.6 \times 10^6$ with a loss of control probability of 8.89×10^{-6}, compared to the fly-by-wire with mechanical backup at $\$8.3 \times 10^6$ with a loss of control probability of 5.8×10^{-6}. This indicates a loss of control ratio of 0.7 in favor of the fly-by-wire with mechanical backup, with a cost ratio of about 0.86. It is for these reasons that the fly-by-wire with mechanical backup was selected as the control system for the MST.

SECTION IV

CONTROL COMPONENT REQUIREMENTS

Since the fly-by-wire system was selected as most appropriate for the MST, requirements for the major components of such a system have been evaluated. These major components consist of the electronics, the command and inertial sensors, gain control, and the servos.

ELECTRONICS

There are two basic electronic computation means available with which to mechanize the required system control laws. These are digital and analog and, of course, a mix of these. The performance levels of both computing methods may be considered adequate. Considering only the control system, analog techniques are recommended. This is due primarily to the lower cost and complexity level of the analog system, compared to the digital system. This, in turn, is primarily due to the fact that a system of this type has inherent analog characteristics such as angular rate and acceleration, pilot control displacement, and output actuator shaft position. The simple straightforward computational requirements of this system simply do not warrant the complexity of digital techniques.

Since the basic system sensors are ac in nature, a common ac-dc signal format is recommended. This implies ac signal transmission and operations with conversion to dc for dynamic operations (signal shaping) and valve operation. This conversion is readily and accurately achievable with present electronics.

The electronics should contribute only those functions built into them. The electronics, exclusive of built-in shaping network, have a frequency response flat, to within ±10 degrees of phase shift, to at least 200 radians per seconds. All redundant functional electronic blocks (such as shaping networks) built into the system shall have predictable characteristics and be matched to within ±2.5 percent of each other. Redundant gain scheduling blocks shall have predictable characteristics and be matched to within ±7.5 percent of each other. From end to end (that is, from sensor input to servo displacement command), redundant electronics blocks shall have predictable characteristics matched to within ±10 percent of each other.

COMMAND SENSORS

Two pilot-control sensor systems are possible. These are redundant force sensors installed in both the pilot's and copilot's column and wheel, or a set of redundant displacement pickoffs placed across the feel bungee. The former system has been proposed for many applications; however, its reliability and mechanizational superiority have yet to be field proven, and its cost is high. It was intended to be used in the F-111 triple-redundant command and stability augmentation system; however, due to qualification problems, it was replaced by a position pickoff system. Such a system has been flight proven in various installations. The installation of a two-axis force transducer in the column and wheel also compromises other normal control functions. The functional advantages of direct force measurement over indirect force measurement have never been clearly defined. For these reasons, an indirect or position pickoff system is proposed. The ac linear variable differential transformer, LVDT, or similar induction-type pickoff is recommended. This type of position pickoff has a failure rate on the order of one tenth that of a resistive element device, potentiometer, or digital-type pickoff. This favorable feature overshadows the advantage of being able to use either ac or dc with the resistive element potentiometer. These pickoffs shall have the following installed performances:

- Combined hysteresis, resolution, and threshold band less than 0.1 percent of the stated range.
- A gradient of input versus output which is linear to within 10 percent of the design range when measured over any 10 percent increment of input.
- The units shall have ranges which are compatible with full column and wheel displacements.

INERTIAL SENSORS

Rate gyros and linear accelerometers are required by the system. With multiple sensor requirements in each axis, packaging becomes a problem. The number of sensors is related to the required degree of redundancy and dispersion requirements determined by battle damage/survivability criteria. Since the latter is beyond the scope of this report, only the implications of the first will be considered. If a four-channel system in each control axis is needed, the sensors might be packaged as follows:

- All sensors for all axes are in one package.
- All sensors for one axis in one package with three different packages.
- One set of sensors for one channel of each axis in one package with four separate, but identical, packages.

The first concept is the most desirable from a logistics point of view. A minimum number of identical packages would be required; however, a single mechanical or electrical failure or a single shot could cause loss of the function in all three axis. In the second concept, each package would be different and, again, a single mechanical or electrical failure or shot could cause loss of the function in the axis concerned. The last concept might not work, because of mismatch due to different package locations, but it is the most desirable, since each package is identical and no single failure can cause the loss of any axis of control. With this concept, care must be taken in mounting the packages, to avoid effects of local vibration environment causing mismatch of redundant sensor outputs. It is also possible that a single location will not be suitable for all sensors in all axes. In such a case, none of the preceding packaging concepts would be suitable.

There are a number of unconventional sensors in the laboratory in the development stage, such as the solid-state vibrational rate gyro. These sensors are not considered far enough advanced in development to be recommended for the baseline fly-by-wire system; therefore, conventional spring restrained rate gyros and linear accelerometers are recommended.

Failure rates on the order of 3.5×10^{-5} for gyros and 2.0×10^{-5} for accelerometers can be expected. These conventional sensors shall have the following general requirements:

- A natural frequency no less than 60 radians per second and a damping ratio between 1 to 0.5.
- A combined hysteresis, resolution, and threshold band less than 0.1 percent of stated range.
- A gradient of input rate or acceleration versus output which is linear to within 10 percent of the design range, measured over any 10 percent increment of input.

The sensors shall have the following stated ranges:

Roll rate:	±100 deg/sec
Pitch and yaw rate:	±20 deg/sec
Pitch acceleration:	-1 to +4 g acceleration
Y-axis acceleration:	±1 g acceleration

GAIN CONTROL

The primary goal of gain adjustments in any control system is to maintain the control system air vehicle gain at a desired level when the air vehicle gain varies. As the response of the air vehicle to applied moments changes as a function of flight condition, it is desirable to alter the gains between the pilot's controls and inertial sensors and the control moment generating devices. There are two basic means available to achieve the required gain adjustments - the open-loop parametric gain adjustment, and the self-adaptive techniques. These two basic techniques are discussed briefly in the following paragraphs.

OPEN-LOOP PARAMETRIC CONTROL

This is conceptually the simplest means of adjusting control system gains. The parameters affecting the response of the air vehicle to applied moments are measured in an open-loop fashion and used to adjust the control system gains. These parameters are normally measurable quantities such as air data and air vehicle configuration parameters. The gain controlling parameter is usually defined in terms of voltage or mechanical position which can be transformed into a voltage. These voltages can be shaped, as required, into nonlinear functions of the parameters represented. The control system signals that require gain scheduling are also in the form of voltages. The gain control and the signal voltages can be fed to an electronic multiplier capable of taking the product to several variables, providing an accurate and flexible means of gain scheduling.

The major problem with the parametric gain scheduling system is the requirement for preknowledge of the response of the air vehicle to characteristics as a function of the gain scheduling parameters. These characteristics will usually be quite well defined, but flight testing must include checking actual flight control system performance against predicted performance.

ADAPTIVE GAIN CONTROL

Honeywell, General Electric, and others have developed several versions of an adaptive controller which used other principles for gain control. One Honeywell controller for the longitudinal mode control automatically compensates for the change in elevator effectiveness without the use of external air data inputs. This is accomplished by maintaining the forward loop gain at a value which forces a pair of complex closed-loop roots to remain near the imaginary axis. The complex roots result from the electrohydraulic servo and load dynamics. The lightly damped oscillation is sensed in the output of the servo, and this information is used to adjust a variable gain element in the controller. To use the technique described, the natural frequency of the oscillation employed must be chosen such that any other vibrational inputs to the system from the rate sensor are not sensed. Also, the servo output amplitude resulting from the oscillation must be small enough so that aircraft motions produced are not evident to the pilot.

Some degree of preknowledge of the aircraft gain characteristics over the flight regime is still required; however, this is generally not considered a problem. The major problem with this gain adjustment concept is its extreme sensitivity to fuselage flexibility. Optimum servo natural frequencies are generally of the same order of magnitude as those of the first fuselage elastic mode. The elastic mode frequencies are affected by fuel loads, dynamic pressure, external and internal stores, and configurations, as are the short-period aerodynamic modes. The problem is one of forcing the self-adaptive oscillation mode to a point between the short-period aerodynamic and first fuselage elastic modes that will not adversely affect either. Again, considerable flight testing is required to verify predicted performance against actual performance. This gain adjustment techniques does not lend itself to input command gain variations, as are required in the control augmentation system; also, feedback phasing of attitude rate signals cannot be readily handled with self-adaptive techniques.

The degree of electronic complexity, "proof" flight testing, and input and feedback gain phasing is comparable between the two gain techniques; therefore, the parametric concept is recommended for the MST control system.

GAIN CONTROL DEVICES

The devices selected are small, individual differential pressure transducers positioning LVDT's, one for each redundant channel. The reason for selection of this technique rather than depending on a central air data computer was to maintain the required redundancy and redundant channel isolation. Four pickoffs on a single shaft in a central air data computer would not have provided acceptable redundancy, and would have posed a signal power and reference interface problem. It is envisioned that the transducers could readily be mounted in convenient locations determined by pneumatic plumbing and wire routing trade-offs.

Few reliability data are available on this type of component; however, it can be considered the equivalent of a pneumatic bellows, a microsyn-type pickoff, two pneumatic joints, and a rugged housing. This combination is estimated to have a failure rate of 7.5 X 10^{-6}/hour. The devices must also have the following performance:

- Linearity of 5.0 percent when measured over any 10 percent increment of input.
- A combined hysteresis, resolution, and threshold no greater than 0.5 percent of rated output.
- A natural frequency of 20 radians per second with a damping ratio between 0.6 and 1.0.

SERVO

The most critical area for a fly-by-wire flight control system is the selection of a suitable means to actuate the control surfaces in proportion to electrical command signals. Intermediate actuators also serve as a final level signal selector or voter; hence, the reliability of the servo actuator chosen must be compatible with the upstream electronics. Consider the following general approaches to the surface actuator problem:

1. Replace conventional hydromechanical surface actuators with some type of electromechanical actuator; i.e., a power hinge coupled to an electric or hydraulic motor through high-performance clutches. This approach requires a long leadtime to develop components with required performance and reliability.
2. Retain conventional hydromechanical surface actuators, and provide the mechanical inputs to the hydraulics surface actuators with secondary servos similar to the series or parallel position servos in automatic flight control systems. Due to the tested performances and reliability of standard tandem surface actuators and the availability of servos, this approach has been selected.

The next problem area is selection of an electromechanical or electrohydraulic secondary servo actuator which is capable of responding to manual input and augmentation input signal frequencies. Electromechanical servos are only marginally acceptable due to their limited ability to meet dynamic requirements. An electromechanical servo consisting of an ac or dc servo motor, gearbox, ball or acme screw, and both rate and position feedbacks can be designed with a sufficient bandwidth for augmentation signals by using an on-off controller or linear controller with compensation. The reliability of such a unit, however, is seriously reduced under cycling conditions. An electromechanical servo actuator concept which could meet the dynamic requirements employs a motor and dual-clutch assembly. The motor is run at a constant velocity. When output motion is commanded, a clutch connects the motor output to a gear train and ballscrew assembly. By the use of gearing and dual clutches, output in both directions is attained. In order to meet the dynamic requirements, a high-response clutch (such as a voice-coil-type clutch developed by Curtiss Wright) is employed. The reliability of the type of clutch noted is doubtful and as yet unproven. In addition, performance of such a clutch is generally unacceptable in a high-temperature environment ($T = 275^{\circ}$ F). Because of the arguments previously cited, only redundant electrohydraulic servos will be conisdered for the study fly-by-wire system.

Of the various servos studied, none appears to present a clear-cut advantage; conversely, none appears to possess a clear-cut disadvantage, compared to the others. One thing is common to all, all were designed as augmentation-type servos intended to be operated in parallel with a hydraulically powered mechanical control system. The outputs of these servos were intended to be mechanically summed with the pilot's mechnical inputs, either directly or through isolating master cylinders. The summed output is then used to control the final power actuator.

All of the proposed or in-current-use designs employ standard two-stage servo valves of a flow control type. Three or four-way cylinders integrate valve flow to provide a linear mechanical output. Position feedback is electrical for some designs, and mechanical for others. All of the currently in-use servos employ a single piston push rod with a single- or dual-tandem piston heads, with single output linkages connecting the unit to the main actuator. The reliability of this system, cylinder body, push rod, rod, piston heads, seals, bearings, and output linkages has been considered very good, compared to such units as electrohydraulic control valves, which have a failure rate approximately 20 times greater. Historically, it has been found that this class of mechanical system can be expected to experience about 2.5 major failures per million flight hours.

With the preceding in mind, the proposed servo is a single system with dual outputs taken from both ends of the piston head. It is controlled by a three or four-way valve, and uses an LVDT electrical feedback. Differential pressure transducers are placed across the piston head. Each of the four servos is fed with an independent hydraulic and electrical supply. The servo outputs are rigidly tied together and control the actuation system valves through dual load paths, summed with the dormant mechanical backup system. The loops are closed through valve drivers which are controlled by the difference between the feedback, the driving, and balancer signals. The system is balanced and monitored by means of the differential pressure transducers. The pressure across the piston heads is measured and fed to a signal selector, along with the pressure from the other piston heads. The output of signal selector is compared with the individual piston head pressures and fed back in a sense to reduce the difference to zero. It is beyond the scope of this study to close the loop with all of the finesse required by real life; however, some of the more important closed-loop features are:

- A natural frequency of at least 60 radians per second, with a damping ratio between 0.6 to 1.0.
- A combined hysteresis, resolution, and threshold no greater than 0.1 percent of rated output.
- A gradient of output versus voltage input which is linear to within 5 percent of design range when measured over any 10-percent increment of input.
- A maximum rate producing full output in 0.5 second.

The system is provided with dual hydraulic cutoff valves. These valves are controlled by the output of the pressure signal selector and the individual pressures. If this signal cannot be reduced below a given level in a given time, the system will be cut off.

SECTION V

HANDLING QUALITIES

All of the candidate systems, except the mechanical system, meet Level 1 flying qualities. In these systems, air vehicle response is sensed and fed back to the aerodynamic control surfaces in a sense to reduce the response. This reduced response is compensated for by added input to the control surface. The net result is a quickened response, with final steady-state value determined by the value of the input divided by the feedback. The systems of interest here are the mechanical plus CASAS and the fly-by-wire systems. The mechanical plus stability augmentation system, while providing Level 1 handling qualities, has been eliminated because the mechanical plus CASAS offers better performance at lighter weight. With these systems, the input commands are in terms of control surface displacements and the feedbacks are the same, only of the opposite sense. The reader is referred to Volume V, Part II, "Simulation Studies/Flight Control System Validation for Verification of Flying Qualities."

In the pitch axis, normal acceleration and pitch rate are sensed. These two signals are fed to the elevator with a gain of 1.66° δe/deg/sec of pitch rate and 10.1° δe/g of normal accelration. Pilot input control is fed to the elevator with a gain of 5° δe/in., to the horizontal stabilizer with a gain of 4° δh/in., and to the spoilers, for DLC, with a gain 24° δs/in., through a washout circuit of $S/(3S + 1)$. The horizontal stabilizer and spoiler gains are reduced to zero as a function of flap setting. The pilot is provided with a switch on the control wheel to open the input to the DLC spoilers at will, and a second interrupt is placed in series with the throttles at full forward. The pilot is also provided with a switch to allow him altitude or flight path angle stabilization. This function is provided with a gain of 0.5 degree of elevator per degree of change in flight path angle and about 0.75 degree per 1,000 feet of altitude. Trim is maintained by a coolie hat switch on the pilot's control wheels. Activation of this switch supplies trim to the horizontal stabilizer at a rate of 2 degrees per second. A function of bank angle is fed to the elevator to compensate for pitch trim changes when in a banked turn. This function is in the form of $\sin \phi \tan \phi$.

In the yaw axis, yaw rate is sensed with a rate gyro, and lateral acceleration is sensed with an accelerometer. These parameters are fed back to the vertical stabilizer with gains of 100 degrees per g and 3.5 degrees per degree per second. The surface deflection due to lateral acceleration is limited to 4.5 degrees, and yaw rate is fed through a washout circuit of $S/(3S + 1)$. The pilot's commands are fed to the vertical stabilizer with a gain of 11.33 degrees per inch of rudder pedal. Trim is maintained by means of a switch on the center console. Activation of this switch results in displacement of the control surface at a rate of 0.6 degree per second.

In the roll axis, roll rate is sensed with a roll rate gyro. This term is fed to the ailerons and outboard spoiler panels with a gain of 0.85 degree per degree per second. The pilot's control wheel deflections are fed to the control surfaces with a gain of 1.0 degree of aileron and spoilers per degree of control wheel. Trim is supplied by the same coolie hat switch as is used for pitch. The trim is fed to the ailerons only at a gain of 2 degrees per second. Synchronized roll attitude is provided with a gain 0.5 degree of the control surfaces per degree change in roll attitude.

With the previously noted gains, the systems all perform essentially the same. The mechanical with CASAS provides control displacements of the control surface through master cylinders and servo displacements, while the two fly-by-wire systems provide displacement through servo displacement. The feedbacks are strictly servo displacements. In all systems, trim is maintained through the proper servos. Figures 15 and 16 present analytical block diagrams of the systems. Level 1 flying qualities are presented in each axis, and the results are presented in the following paragraphs.

In the longitudinal axis, the short-term dynamics are essentially the same for both takeoff with 46 degrees of flaps and 71 knots, and landing with 73 degrees of flaps and 65 knots. The natural frequency of the short-period responses is approximately 5.75 radians per second, and the damping is approximately 1. The long-period or phugoid mode has a natural frequency of 0.08 radian per second and a damping ratio of at least 0.2. In the lateral directional axis, the dutch roll mode provides a natural frequency of 0.4 radian per second for takeoff, and 1.3 radians per second for landing; the damping is about 0.6 and 1.0, respectively. The spiral mode time constant is about 13.5 seconds for the takeoff, and about 18 seconds for landing. The roll axis control effectiveness, in terms of the time required to change the bank angle by 30 degrees, is about 1.4 seconds in both cases. The roll rate time constant is less than 1 second in both cases. The directional stability of the aircraft, with respect to the sideslip excursion parameter, is well within the Level 1 requirement of 0.3 at $\psi\beta = -85°$. All of these parameters readily meet the Level 1 flying qualities presented in Volume V, Part II, of this report.

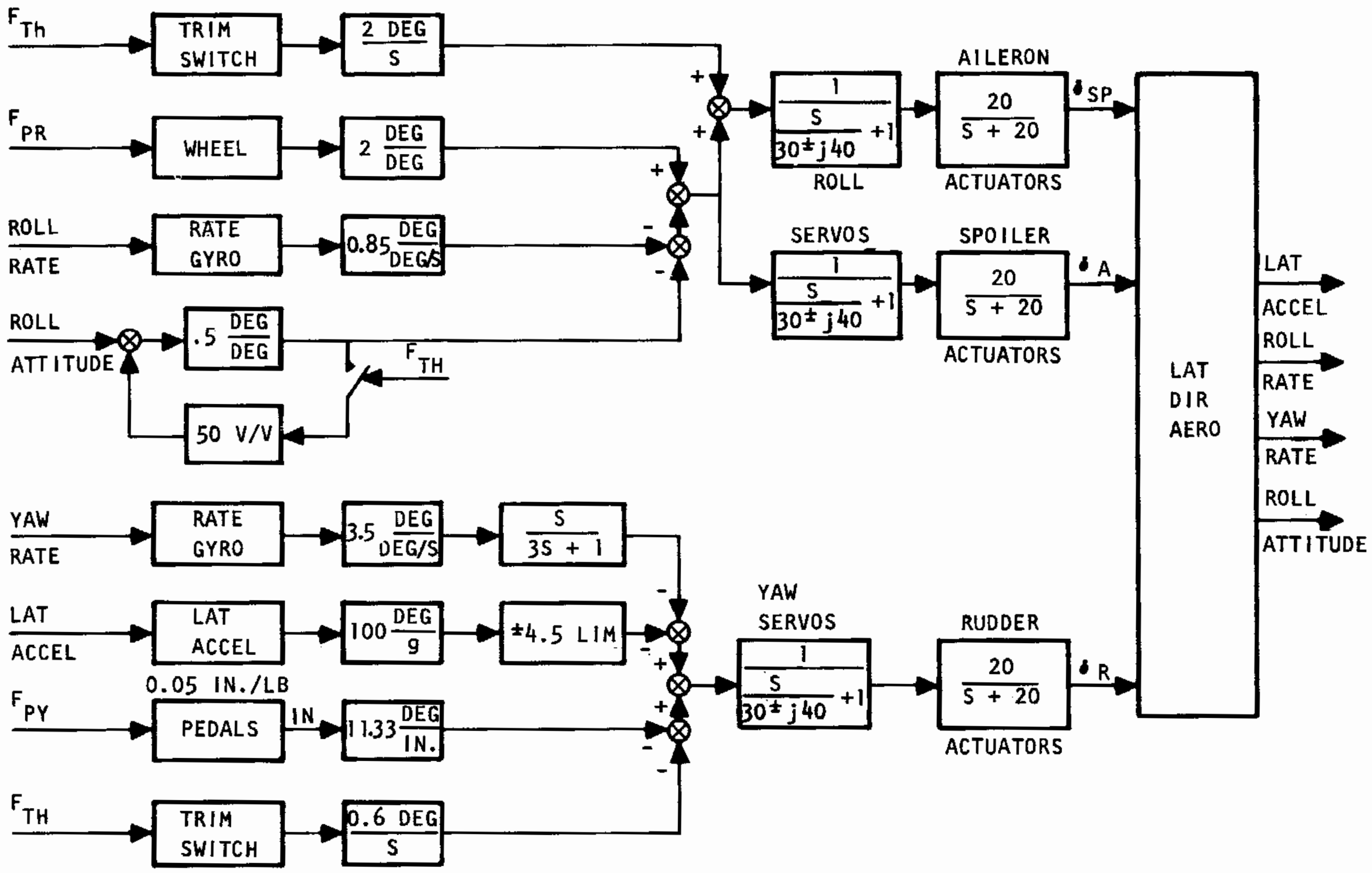


Figure 15. Roll and Yaw Axes of Control

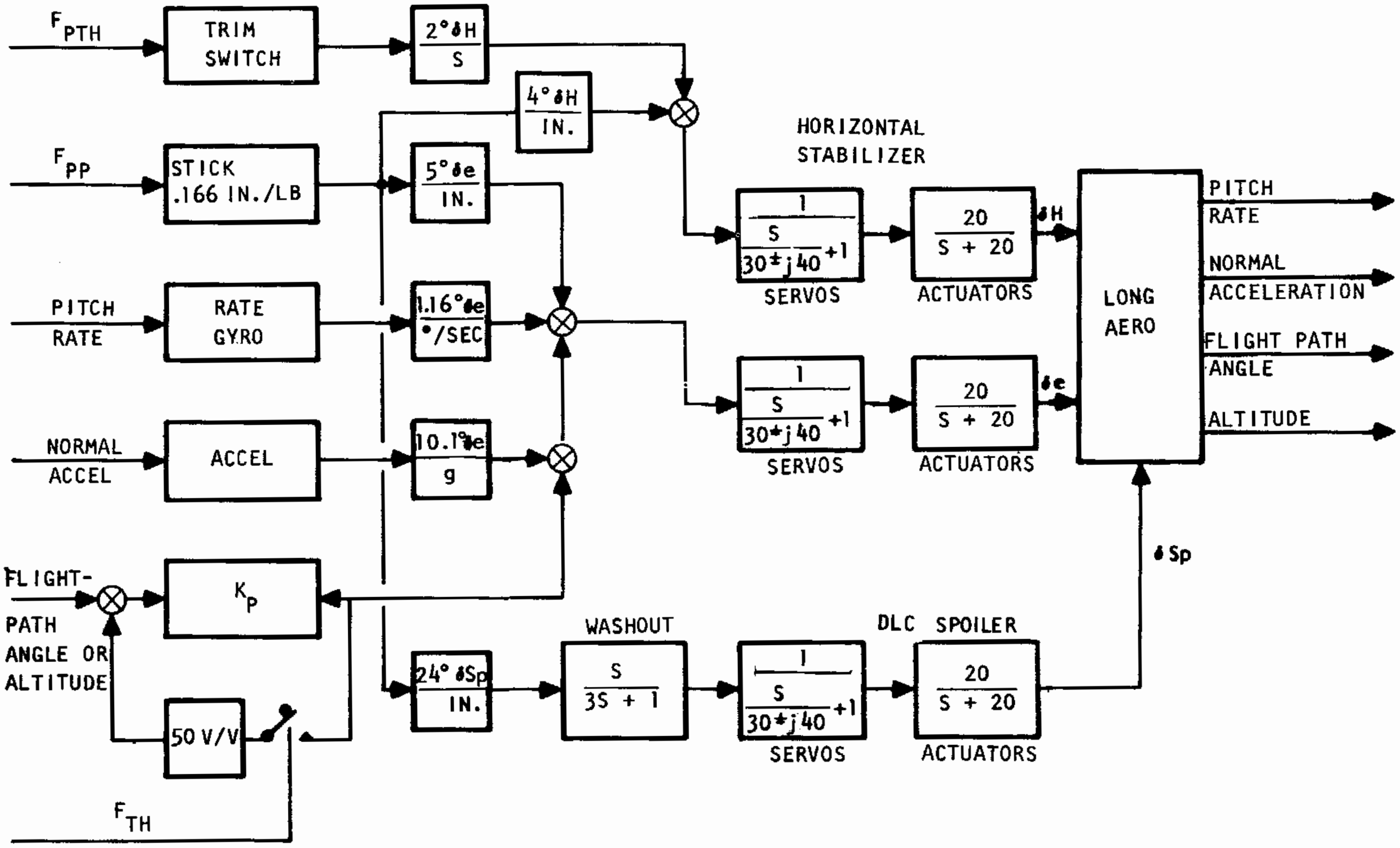


Figure 16. Pitch Axes of Control

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Mechanization of a fly-by-wire control system that is capable of meeting realistic performance, flight safety, and mission success requirements can be achieved, assuming applicability of available component failure rate data. This can be achieved with a system using four channels of sensors and electronics, with four servos using four independent hydraulic systems. These servos may be either force or position summed. If force summation is used the valves must be electronically balanced, requiring pressure transducers. If the summation is position, additional position transducers located at the summation point must be used and fed back to the individual servos to reduce the transient in the event of a failure. The position-summed servos must have at least 50 percent authority so that at 100 percent authority will be retained after two failures. Duality of the output is a must, and override bungees will be required of the position-summed servos to preclude overstressing of the power actuator valves with the normal 200 percent authority. If the available control system failure rate data is applicable, this control system coupled with normal cockpit controls and at least triply redundant power actuation system, powered by individual hydraulic supplies, can be expected to turn in a loss of control failure rate less than 10^{-5} for a 5-hour mission.

Available failure rate data, however, does not include events that may lead to unpredictable failures. These events include utilization of improper system or component failure rates, environmental conditions not as predicted with resultant multiple or nonrandom failures, inadequate monitoring to insure against unknown failures in redundant components, and unforeseen failure modes. It is for these reasons that a four-channel system with force summed servos, coupled in the pitch and roll axes with a normally dormant single mechanical control system, is being recommended for the MST. The normally dormant mechanical control system would provide the MST's crew with a means of getting home in the event of an unforeseen, or foreseen, fly-by-wire control system failure.

Since fly-by-wire systems offer promise for application in future operational aircraft, it is recommended that their development continue to be pursued. To this end, it is recommended that the operational utilization include:

1. A set of normally dormant single mechanical control systems as a backup in the first generation of fly-by-wire operational control systems, for the pitch and roll axes.

2. Extended application of available maintenance, accident, incident, and abort rate data to the definition of realistic operational component failure rates for future control systems utilization.

3. Development of high flow rate electrohydraulic valves suitable for direct electrical control of fly-by-wire surface control power actuators be continued.

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13. ABSTRACT

The basic objective of the work reported herein was to provide a broader technology base to support the development of a medium STOL Transport (MST) airplane. This work was limited to the application of the externally blown flap (EBF) powered lift concept.

The technology of EBF STOL aircraft has been investigated through analytical studies, wind tunnel testing, flight simulator testing, and design trade studies. The results obtained include development of methods for the estimation of the aerodynamic characteristics of an EBF configuration, STOL performance estimation methods, safety margins for takeoff and landing, wind tunnel investigation of the effects of varying EBF system geometry parameters, configuration definition to meet MST requirements, trade data on performance and configuration requirement variations, flight control system mechanization trade data, handling qualities characteristics; piloting procedures, and effects of applying an air cushion landing system to the MST.

From an overall assessment of study results, it is concluded that the EBF concept provides a practical means of obtaining STOL performance for an MST with relatively low risk.

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