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HYDROFLUIDIC STABILITY AUGMENTATION SYSTEM (HYSAS) OPERATIONAL SUITABILITY DEMONSTRATION

Honeywell Inc.
1625 Zarthan Avenue
St. Louis Park, Minnesota 55416

October 1977

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Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report presents the results of a joint Army/Navy program to demonstrate the reliability and maintainability characteristics of a Hydrofluidic Stability Augmentation System (HYSAS) under typical military operating conditions. The report describes the installation and operation of the single-axis (yaw) HYSAS on Navy TH-57 helicopters and the two-axis (roll, yaw) HYSAS on Army OH-58 helicopters, problems encountered, and the solution of these problems. Predicted reliability of the HYSAS and electromechanical helicopter SCAS is computed (from measured data), presented, and compared. The program has demonstrated the operational suitability of the HYSAS and the extremely high reliability and maintainability capabilities of fluidic systems.

Mr. George W. Fosdick of the Systems Support Division served as the project engineer for this effort.

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Hydrofluidic stability augmentation systems (HYSAS) were evaluated in operational military helicopters for 1-1/2 years to establish a measure of maintainability and reliability for this relatively new technology. Design details, manufacturing problems encountered, installation experiences, and operational problems are discussed. Reliability predictions for fluidic systems and a similar electronic stabilization system are also presented.

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PREFACE

This document is the final report on a joint Army/Navy program to establish the suitability of fluidic systems to operate in military aircraft while receiving standard military maintenance. The program was administered under the direction of the Eustis Directorate,* U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, with Mr. George W. Fosdick as Project Engineer. Project monitors for the Naval Air Development Center, Warminster, Pennsylvania, were Mr. Horace B. Welk, Jr. and Mr. Edward T. Schmidt.

*On 1 September 1977, the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory was redesignated the Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM).

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SECTION I
INTRODUCTION

Hydrofluidic stability augmentation systems (HYSAS) have, in several Army sponsored programs, demonstrated their capability to enhance the flying qualities of helicopters. The objective of this program was to establish the reliability and maintainability characteristics of fluidic systems under typical Army and Navy operational conditions.

Design of the yaw axis system is reported in Reference 1, while flight test of this system is reported in Reference 2. Development of the roll axis system is reported in Reference 3.

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1. Harvey D. Ogren, Hydrofluidic Yaw SAS Analysis Design and Development, Government and Aeronautical Products Div., Honeywell Inc., USAAMRDL TR 74-7, Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, March 1974, AD777804.

2. Harvey Ogren, Donald Sotanski, LeRoy Genaw, Yaw Axis Stability Augmentation System Flight Test Report, Government and Aeronautical Products Div., Honeywell Inc., USAAMRDL-TR-74-39, Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, June 1974, AD784134.

3. Darroll Bengston, Thomas Dickovich, Robert Helfenstine, Roll-Axis Hydrofluidic Stability Augmentation Systems Development, Government and Aeronautical Products Div., Honeywell Inc., USAAMRDL-TR-75-43, Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, September 1975, AD016929.

This report describes the design changes that were made to the system cited above and the problems that were encountered in fabricating and calibrating 46 controllers. A yaw axis stabilization kit was designed for the TH-57 helicopter, and a two-axis stabilization kit was designed for the OH-58 helicopter. Field problems encountered during installation and 1-1/2 years of operation are discussed. Most significant is the data relative to reliability and maintainability of fluidic systems.

SECTION II
CONTROL SYSTEM COMPONENTS

Components fabricated and tested for the HYSAS Operational Suitability Demonstration Program are nearly identical to those developed and flight tested on the previous Army sponsored programs discussed in Section I. This section describes the physical configuration of operational suitability hardware, design changes, fabrication problems, and component test data.

YAW AXIS CONTROLLER CONFIGURATION

Figure 1 is a schematic of the yaw axis controller. Helicopter yaw rate is measured by a vortex rate sensor (VRS), amplified by amplifiers A1 and A2, high passed using series bellows capacitors, and amplified again by a double amplifier, A4. A small portion of the rate signal bypasses the high-pass capacitors through resistors R22 and R23. The transfer function of this rate signal is

$$\frac{\Delta P \text{ out}}{\text{rate in}} = \left[0.135\left(\frac{2.5S}{2.5S+1}\right) + 0.027\right] e^{-0.06S} \text{ psid/deg/sec} \qquad (1)$$

A second input into this controller, the pilot input device (PID), allows the controller to damp out external disturbances without counteracting pilot inputs. A cable from the rudder pedal linkage moves the PID flow divider, whose output is lagged by capacitor C5 and amplified by amplifier A3. With ideal gains and shaping, the signal at the output of A3 for a specific pilot command will be equal to and opposite in polarity from the resulting rate signal at the output of amplifier A2. For a pilot command, the net effect change at amplifier A4 should be nearly zero. Transfer function of this pilot loop is

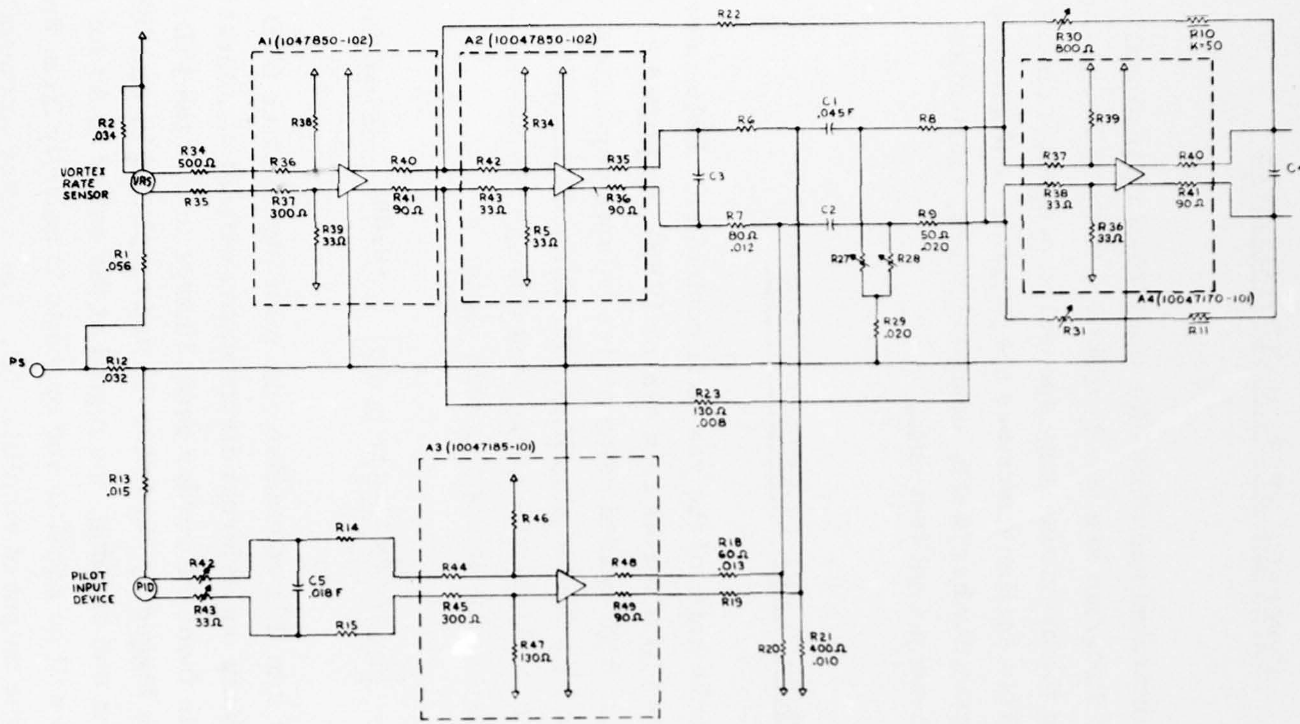

Figure 1. C13736AA01 (Yaw Axis Controller) Schematic.

$$\frac{\Delta P \text{ out}}{\text{cable travel input}} = 45.2 \left(\frac{1}{S+1}\right)\left(\frac{2.5S}{2.5S+1}\right) \frac{\text{psid}}{\text{in. of cable}} \qquad (2)$$

These transfer functions and schematics of them are discussed in References 1 and 2.

Figure 2 is an assembly drawing of the controller, Table 1 is the parts list, and Figure 3 is an exploded view of the major components. After assembly and test, the controller is bolted to a servoactuator. Side and top views of the completed assembly are shown in Figures 4 and 5, respectively.

ROLL AXIS CONTROLLER CONFIGURATION

Configuration of the roll axis controller is nearly identical to that presented in Reference 3. Figure 6 is a schematic of the roll axis controller. Output of the VRS is amplified by A1 and A2, shaped by a two-second lag using C1, high passed through series capacitors C2 and C3, and amplified again through double amplifier A3. The transfer function of the roll axis controller is

$$\frac{\Delta P \text{ out}}{\text{rate in}} = 0.266 \left(\frac{10S}{10S+1}\right)\left(\frac{1}{2S+1}\right) e^{-0.06S} \text{ psid/deg/sec} \qquad (3)$$

Figure 7 is an assembly drawing of the roll axis controller, and Table 2 is the parts list. Figure 8 is an exploded view of the main components, and Figure 9 shows a completely assembled controller.

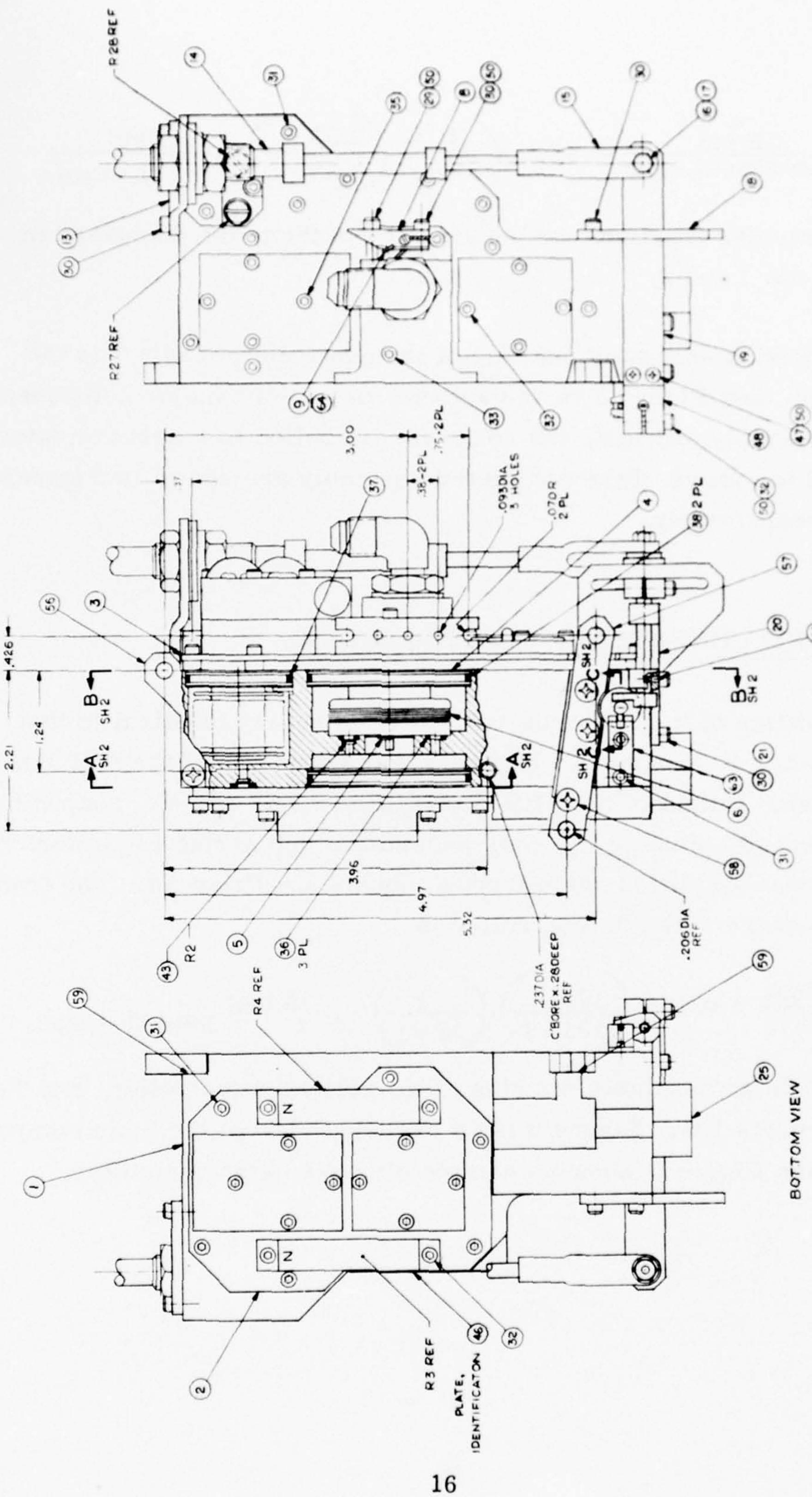

Figure 2. YG1143 Yaw Axis Controller Assembly Drawing.

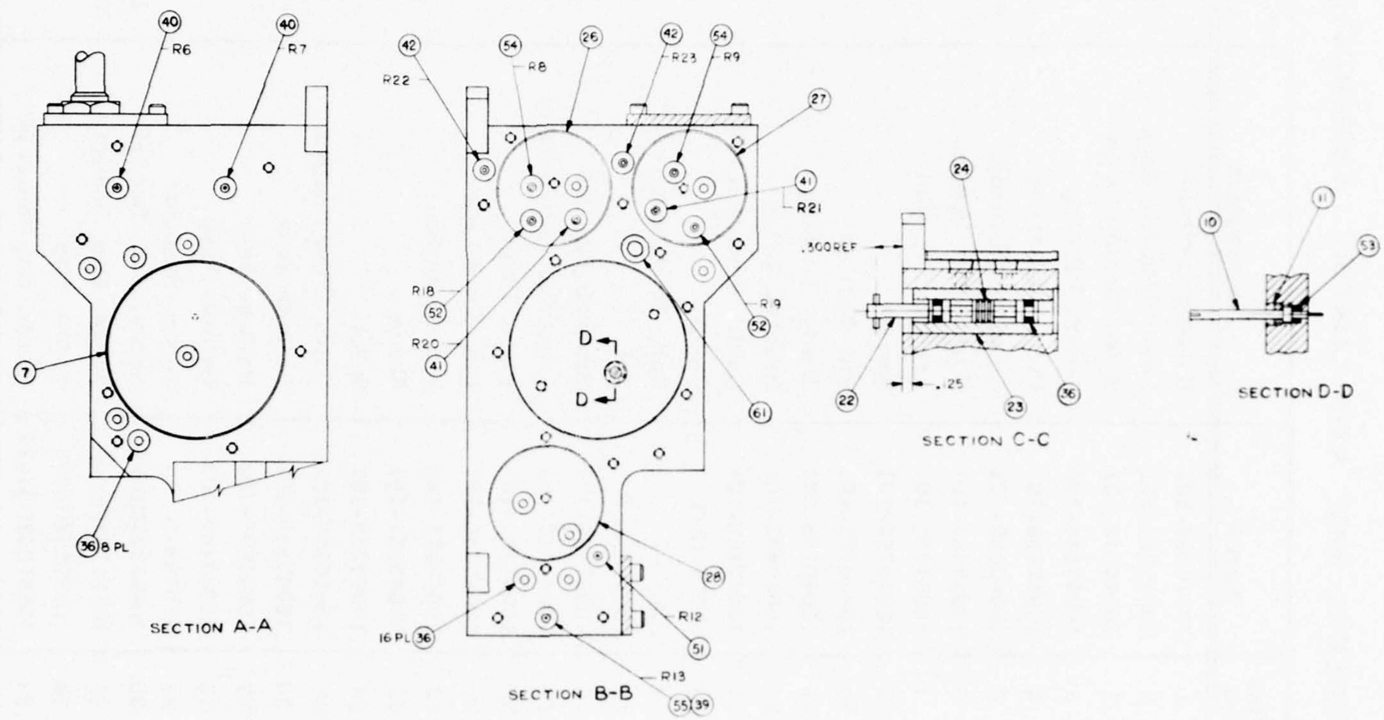

Figure 2. YG1143 Yaw Axis Controller Assembly Drawing (Concluded).

TABLE 1. YAW AXIS CONTROLLER PARTS LIST

Find No.	Part No.	Description	Qty
1	10046948-101	Housing Controller	1
2	10047851-101	Lower Manifold Assy	1
3	10047846-101	Upper Manifold Assy	1
4	10047446-101	Cover, VRS Top	1
5	10047498-101	Pickoff Assembly	1
6	10040030-101	Coupling, Element	AR
7	10047447-101	Cover, VRS Bottom	1
8	10047435-101	Lock Lever, Null	1
9	10049202-101	Spring	1
10	10040762-101	Pin, Null Adj	1
11	10040763-101	Sleeve, Locking	1
13	10047442-101	Bracket, Cable	1
14	10047183-101	Cable, Push Pull Cont	1
15	MS35812-1	Clevis	1
16	AN3C-6	Bolt, Machine Aircraft	1
17	NAS1291C3	Nut	1
18	10047444-101	Bracket, Support	1
19	10047443-101	Arm, Spool Adjustment	1
20	10047439-101	Plate, Pivot	1
21	10047440-101	Pin, Spool Link	1
22	10047441-101	Pin, Spool End	1
23	10040251-101	Sleeve	1
24	10040250-101	Spool	1
25	10047182-101	Valve, Flow Control	1
26	10047449-101	Bellows Assy	1
27	10047449-102	Bellows Assy	1
28	10047449-103	Bellows Assy	1
29	960783-5	Screw, Shoulder	1
30	NAS1352C04-4	Screw, Cap, Soc Hd	11
31	NAS1352C04-6	Screw, Cap, Soc Hd	19
32	NAS1352C04-8	Screw, Cap	2
33	NAS1352C04-14	Screw, Cap Socket Hd	1

TABLE 1. YAW AXIS CONTROLLER PARTS LIST (Concluded)

Find No.	Part No.	Description	Qty
34	Not Used		
35	NAS1352C04-24	Screw, Cap Socket Hd	1
36	MS28775-005	Packing Preformed "O" Ring	29
37	MS28775-025	"O" Ring	3
38	MS28775-133	"O" Ring	2
39	MS28775-007	"O" Ring	3
40	10047089-113	Orifice	2
41	10047089-102	Orifice	2
42	10047089-112	Orifice	2
43	10047089-130	Orifice	1
44	461824-2	Pin	1
45	Not Used		
46	435100	Plate, Identification	1
47	NAS662C2R4	Screw, Machine	2
48	10049198-101	Clevis, Adjustment	1
49	Not Used		
50	MIL-S-22473	Sealant	AR
51	10047089-128	Orifice	1
52	10047089-115	Orifice	2
53	MS28775-004	"O" Ring	2
54	10047089-106	Orifice	2
55	10047089-116	Orifice	1
56	10049199-101	Hanger, Mounting	1
57	10049200-101	Bar, Mounting	1
58	MS24693-C27	Screw, Flat Head	5
59	MC7777-02	Adhesive	AR
60	Not Used		
61	MS28775-008	"O" Ring	1
62	Not Used		
63	10049570-101	Guide	1
64	10050033-101	Bushing, Spring	1

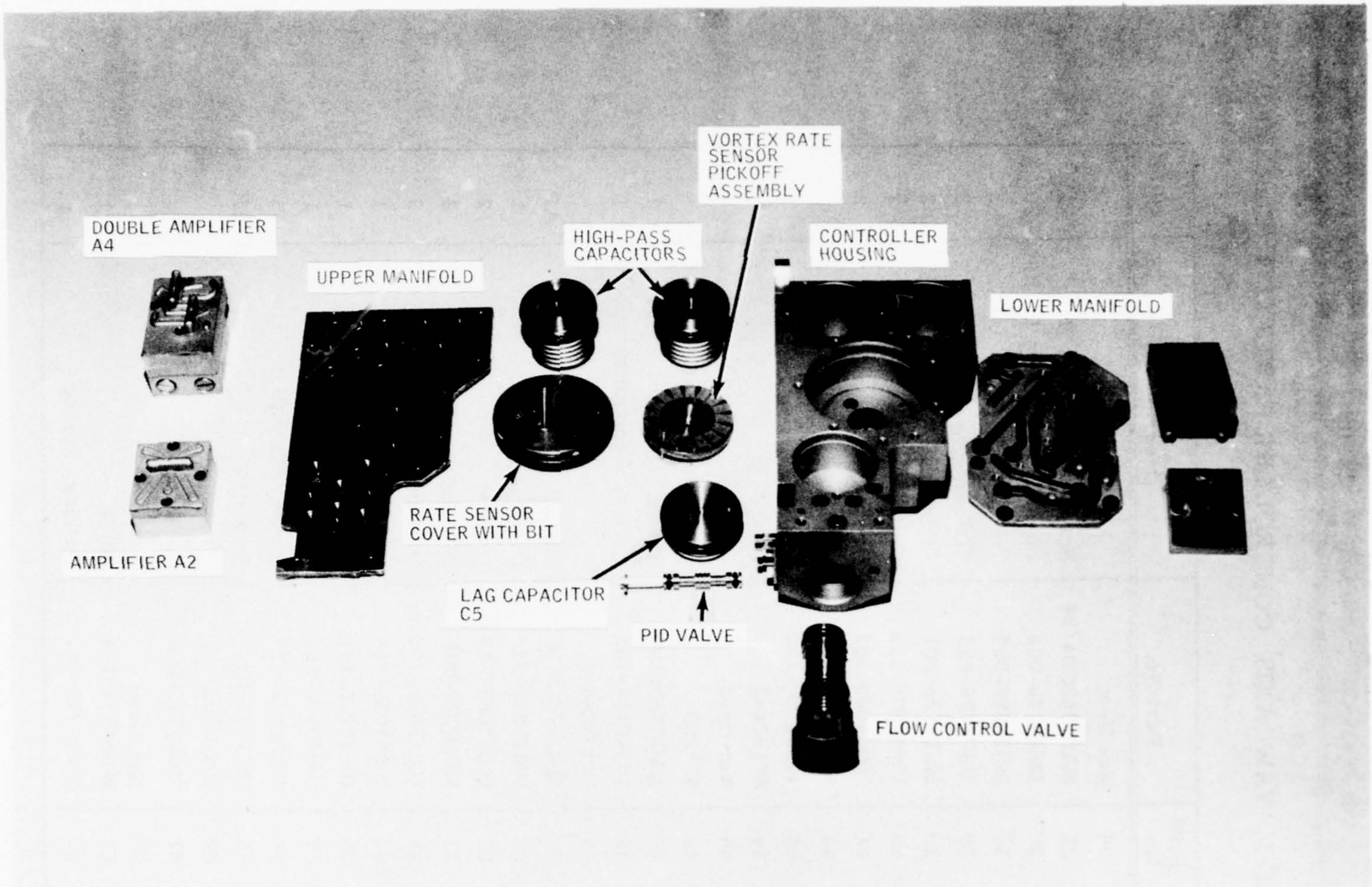

Figure 3. YG1143 - Yaw Axis Controller Exploded View.

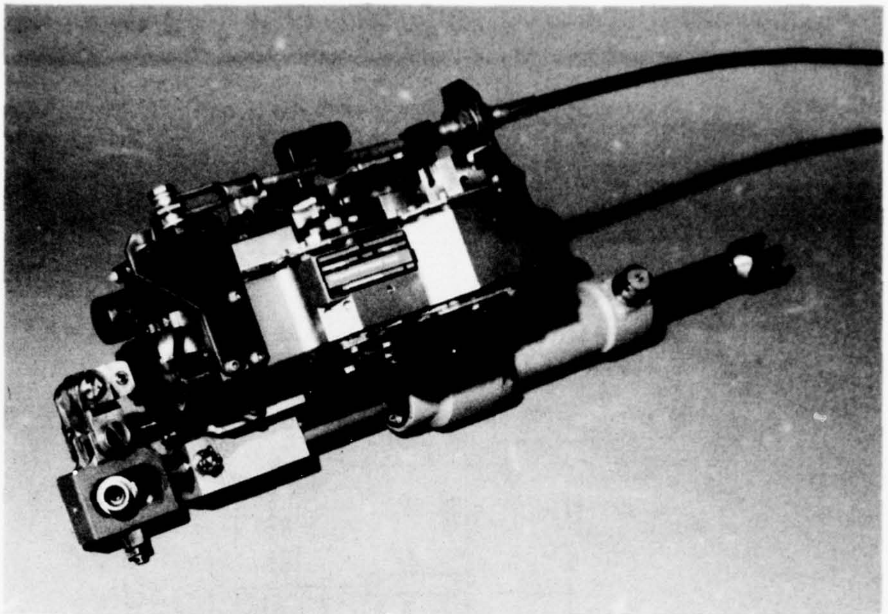

Figure 4. Yaw Axis Controller Servoactuator Assembly - Side View.

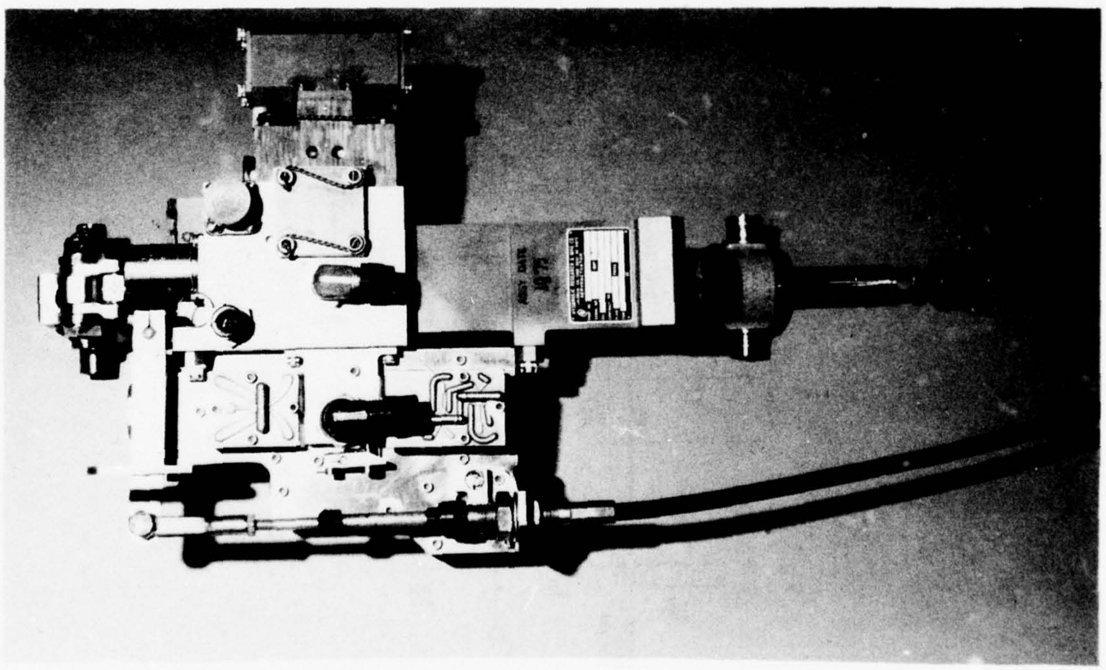

Figure 5. Yaw Axis Controller Servoactuator Assembly - Top View.

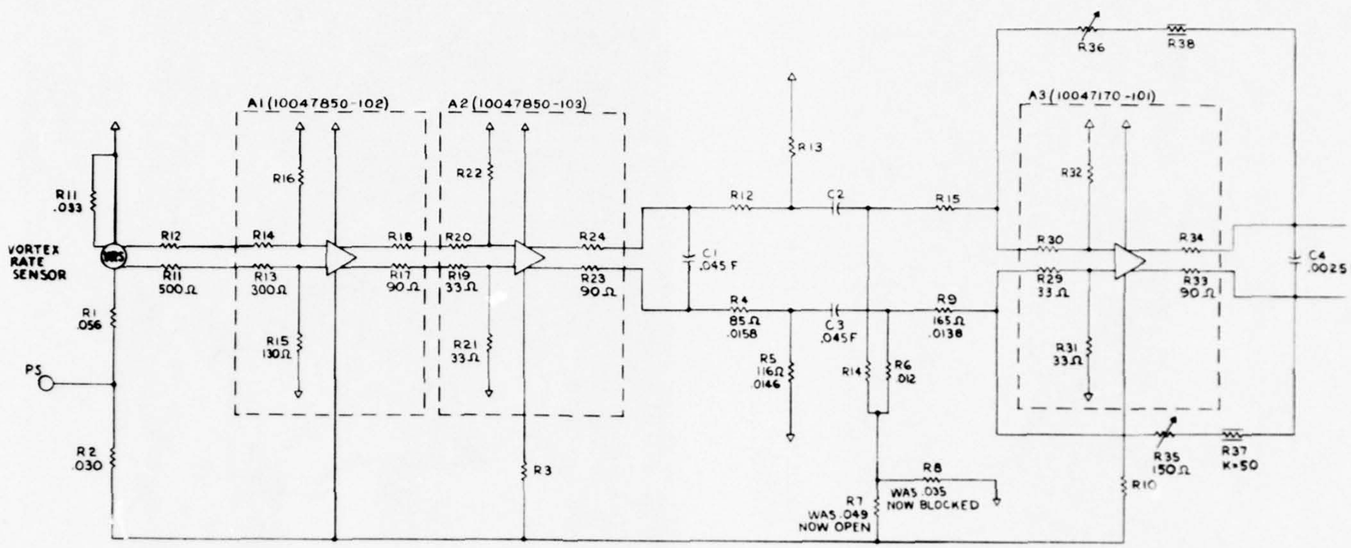

Figure 6. C13753AA01 (Roll Axis Controller) Schematic.

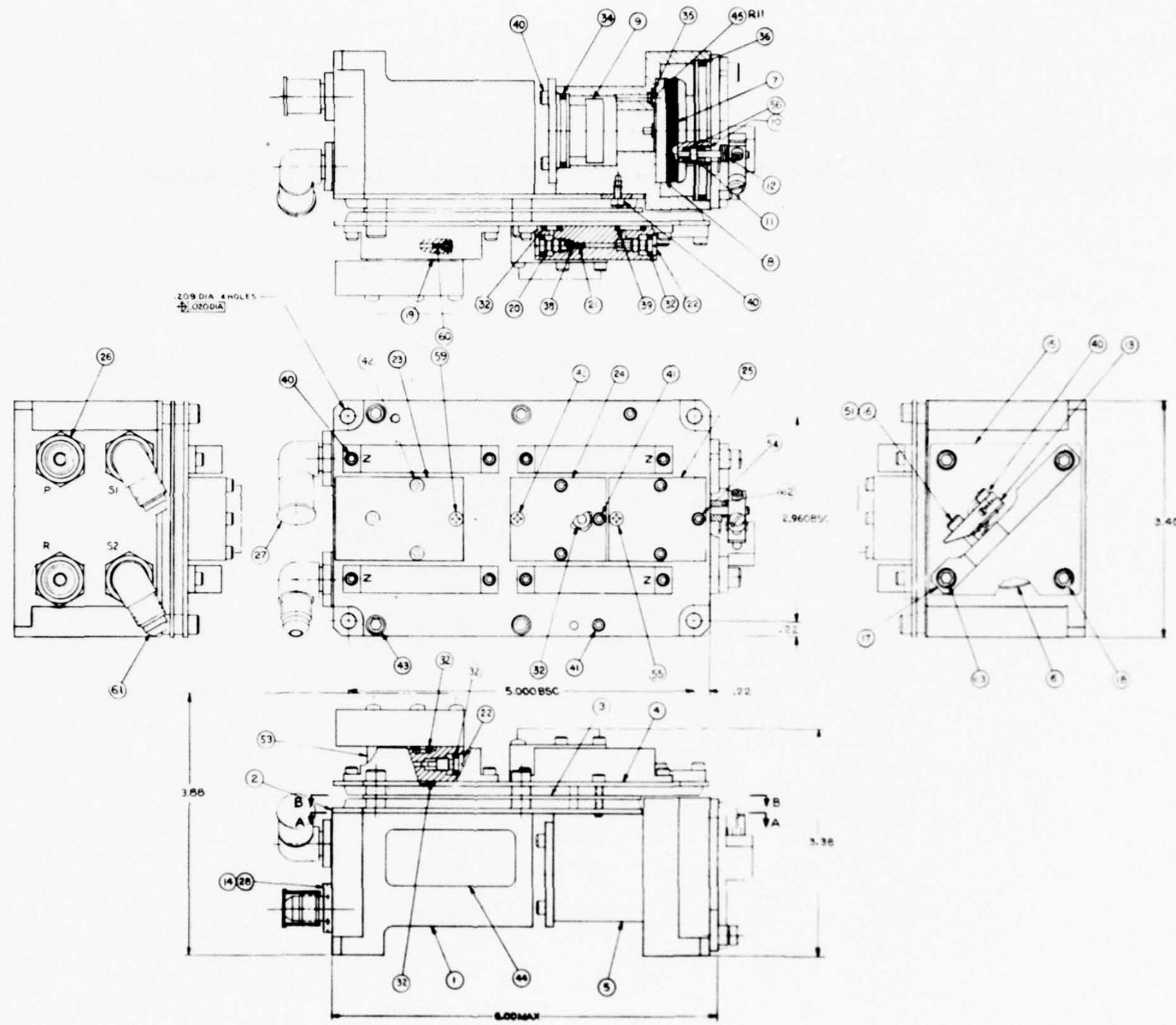

Figure 7. YG1136A Roll Axis Controller Assembly Drawing.

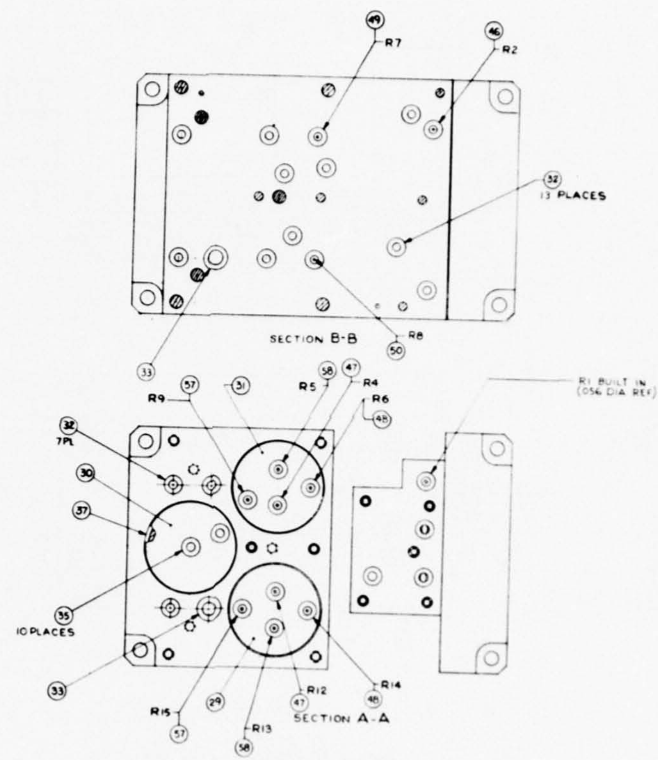

Figure 7. YG1136A Roll Axis Controller Assembly Drawing (Concluded).

TABLE 2. ROLL AXIS CONTROLLER PARTS LIST

Find No.	Part No.	Description	Qty
1	10049056-101	Block, Capacitor	1
2	10047454-101	Manifold, Lower	1
3	10049045-101	Plate, Spacer	1
4	10047451-101	Manifold, Upper	1
5	10049046-101	Housing	1
6	10047446-101	Cover, VRS Top	1
7	10040030-101	Coupling, Element	AR
8	10047498-101	Pickoff Assembly	1
9	10049194-101	Cover, Plenum	1
10	10040763-101	Sleeve, Locking	1
11	10040762-102	Pin, Null Adj	1
12	10049202-101	Spring	1
13	10047435-101	Lock Lever, Null	1
14	MS28778-4	Packing, Preformed	4
15	10049203-101	Plate, Hold Down	1
16	960783-5	Screw, Shoulder	1
17	10049204-101	Bar, Hold Down	1
18	NAS1352C08-6	Screw, Cap	4
19	10040764-101	Block, Feedback - Single	4
20	10047173-101	Clamp, Viscous Orifice	4
21	10049557-103	Viscous Resistor	2
22	10047484-101	Valve, Needle	6
23	10047170-101	Assembly Amplifier	1
24	10047850-103	Amplifier Assy	1
25	10047850-102	Amplifier Assy	1
26	10049196-101	Filter, Fitting	1
27	M5501/3-R4	Dust Cap	4
28	MS21900J4	Union, Flared	1
29	10047449-106	Bellows Assy	1
30	10047449-104	Bellows Assy	1
31	10047449-105	Bellows Assy	1
32	MS28775-007	"O" Ring	59

TABLE 2. ROLL AXIS CONTROLLER PARTS LIST (CONCLUDED)

Find No.	Part No.	Description	Qty
33	MS28775-009	"O" Ring	2
34	MS28775-021	"O" Ring	1
35	MS28775-005	Packing Preformed "O" Ring	13
36	MS28775-133	"O" Ring	1
37	MS28775-025	"O" Ring	3
38	MS28775-001	Packing	4
39	MS28775-010	"O" Ring	4
40	NAS1352C04-4	Screw, Cap Soc Hd	17
41	NAS1352C04-10	Screw, Socket Head	3
42	NAS1635-04-15	Screw, Machine	4
43	NAS1352C08-10	Screw, Socket Head	4
44	435100	Plate, Identification	1
45	10047450-102	Orifice	1
46	10047089-127	Orifice	1
47	10047089-104	Orifice	2
48	10047089-113	Orifice	2
49	10047450-101	Orifice	1
50	10047089-118	Orifice	1
51	PC4927-01	Apply	AR
52	MIL-S-22473	Sealant	AR
53	10049201-101	Block, Shunt	1
54	NAS1352C04-6	Screw, Socket Hd	3
55	NAS1635-04-14	Screw, Pan Head	1
56	MS28775-004	"O" Ring	1
57	10047089-114	Orifice	2
58	10047089-116	Orifice	2
59	NAS1635-04-26	Screw	1
60	10049557-104	Viscous Resistor	2
61	MS5152784	Elbow	2
62	10050033	Bushing, Spring	1
63	NAS1352C08-8	Screw, Cap	2

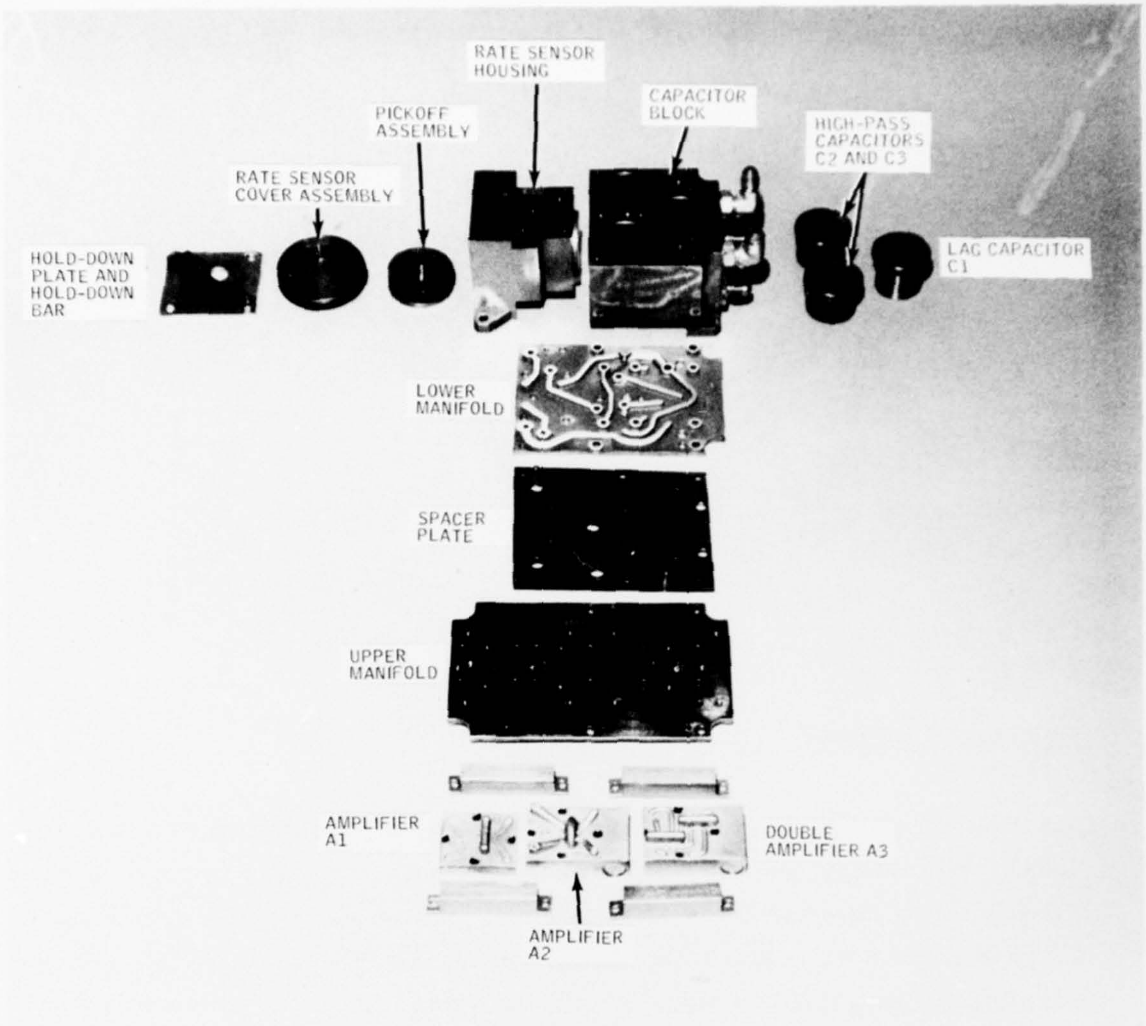

Figure 8. YG1136A - Roll Axis Controller Exploded View.

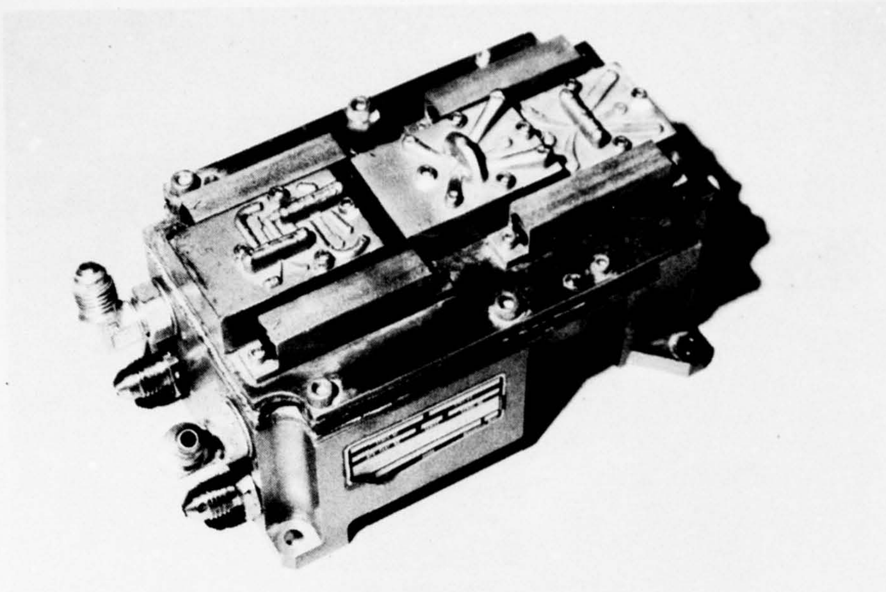

Figure 9. Roll Axis Controller Assembly.

SERVOACTUATORS

One directional servoactuator and two cyclic servoactuators are used on the OH-58 installation; only the directional servoactuator is used on the TH-57. Two views of the directional servoactuator coupled with a yaw axis controller were shown in Figures 4 and 5. A pair of cyclic servo-actuators is shown in Figure 10. Right- and left-hand servoactuators are identical except for port locations.

Configuration and performance of the directional servoactuator are similar to those the servoactuator flight tested under Contract DAAJ02-72-C-0111. Design changes implemented for this operational suitability program were:

- A new summing linkage design was incorporated into the servo-actuator. This linkage was expected to eliminate problems experienced with the former linkage.

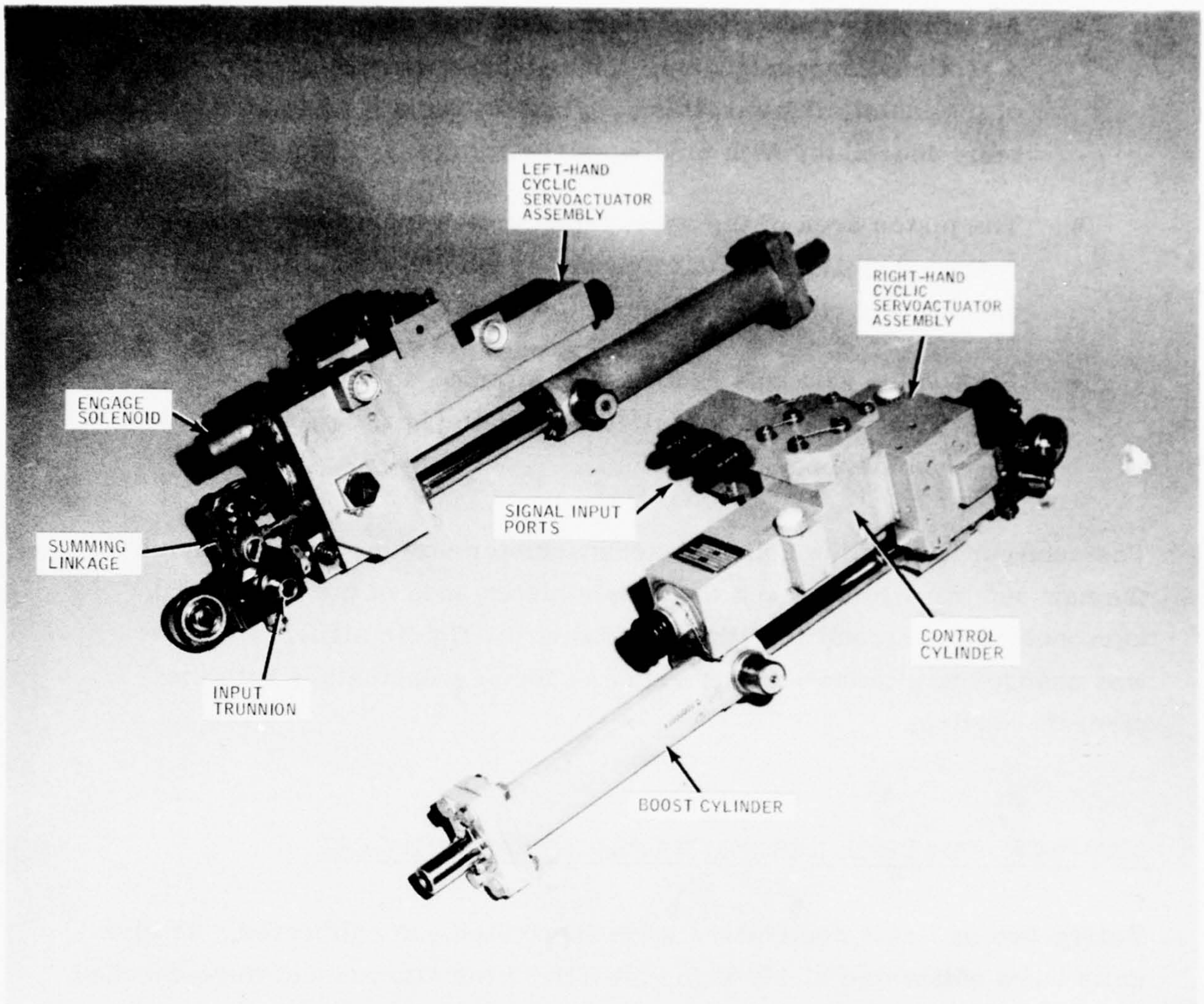

Figure 10. Cyclic Servoactuators.

- An optional antirotational mechanism was designed for the directional servoactuator. This linkage was not used in either of the installations on this program because it aggravated problems associated with binding of the summing linkage.

- The piston area of the servoactuator was increased. This change was designed to improve threshold, resolution, and null hunting characteristics of the servoactuator.

- Pilot valve gain was reduced to eliminate an interaction effect that caused a so-called "tail rotor buzz" problem under some unusual conditions.

The configuration of the roll axis servoactuator was modified to include the new summing linkage and the larger piston area of the directional servoactuator. In addition, the location of the fluidic signal input ports was changed to eliminate interference of the servoactuators with the aircraft cowling.

YAW AXIS CONTROL SYSTEM FABRICATION AND TEST

Thirty-two yaw axis controllers were fabricated and calibrated. Twelve units were calibrated at 170°F for the TH-57 installation and were checked at 120°F. The nominal specified hydraulic fluid operating temperature for the TH-57 is 50°F hotter than it is for the OH-58; this is the reason for the slight differences in the two units. Required gain and dynamics are the same for both applications. The calibration and flightworthiness testing results of the TH-57 yaw axis systems (KG1216AA) are presented in Section I of the HYSAS Operational Suitability Demonstration Data Package. (This Data Package can be obtained from the Eustis Directorate.) Fourteen OH-58 controllers and six qualification units were calibrated at 120°F to the OH-58 requirements and were checked at 180°F. The OH-58 yaw axis controller calibration results are presented in Section II of the Data Package, which covers calibration and flightworthiness testing of the KG1217AA two-axis OH-58 hydrofluidic damper system. The qualification task was eliminated because funds were reallocated. Fabrication and calibration of the yaw axis controllers are summarized in the following paragraphs.

Rate sensor pickoff null offset was as large as 500 degrees per second in some cases, with little or no correlation between the offset and physical differences in pickoff geometry. After several minor errors were discovered in fabrication of the rate sensor, closer quality control was maintained in the electroforming process; however, offsets were still frequently greater than 200 degrees per second. YG1143A02 yaw axis controllers for the TH-57 aircraft used this initial design, and each unit was nulled with a bias orifice at the output of the rate sensor. Average bias orifice size was 0.015 inch in diameter. Section I of the Data Package includes a tabulation of calibration orifices on the YG1143A02 yaw axis controller. The controller with the smallest diameter bias orifice is the one with the greatest rate sensor offset.

A four-port rate sensor pickoff developed on another program showed promise of having a much lower average null offset than the two-port pickoff used on the YG1143A02 (TH-57) yaw axis controllers. Null offset and its variation with temperature was more critical on roll because of its higher gain; therefore, a four-port pickoff was designed that was compatible with the roll axis controller. The YG1143A01 (OH-58) yaw axis controller housing was modified to accept this new four-port pickoff. Offset of the four-port pickoff was substantially smaller than that of the two-port design, as evidenced by the calibration data on the YG1143A01 yaw axis controller, which is given in Section II of the Data Package. Average bias orifice diameter was about 0.026 inch, three times larger than that of the two-port pickoff. This same four-port pickoff design was later fabricated under another program; its performance is tabulated in USAAMRDL-TR-77-2.[4] Based on a sample of 20 sensors, the maximum flow-loaded offset was 70 degrees per second.

During fabrication and testing, several problems were experienced with the pilot input device (PID). The close tolerance hole in the yaw axis controller main housing which accepts the PID sleeve was slightly oversize due to an improper anodizing procedure. New oversize sleeves were fabricated, and the original sleeves were "sold" to the producibility program. Leakage between the sleeve and housing was excessive when the original fabrication method was used. Modifications to the assembly prodecure included the use of a shrink fit and epoxy sealing rings.

Under some conditions internal leakage occurred around the orifice restrictors, resulting in inconsistent calibration data. The configuration of the orifice installation is shown in Figure 11. The 0.005-inch-thick shim was added to maintain tighter contact between the "O" ring and the orifice cap. This general configuration is not recommended for future designs.

Spring rate checks made by receiving inspection showed that the spring rate of the purchased bellows (fluidic capacitors) was higher than specification. One-hundred percent inspection was required to ensure that all bellows were within specification limits.

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(4) Walter Posingies, Production Suitability of an Electroform Conductive Wax Process for the Manufacture of Fluidic Systems, Government and Aeronautical Products Div., Honeywell Inc., USAAMRDL-TR-77-2, Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, April 1977, AD038562.

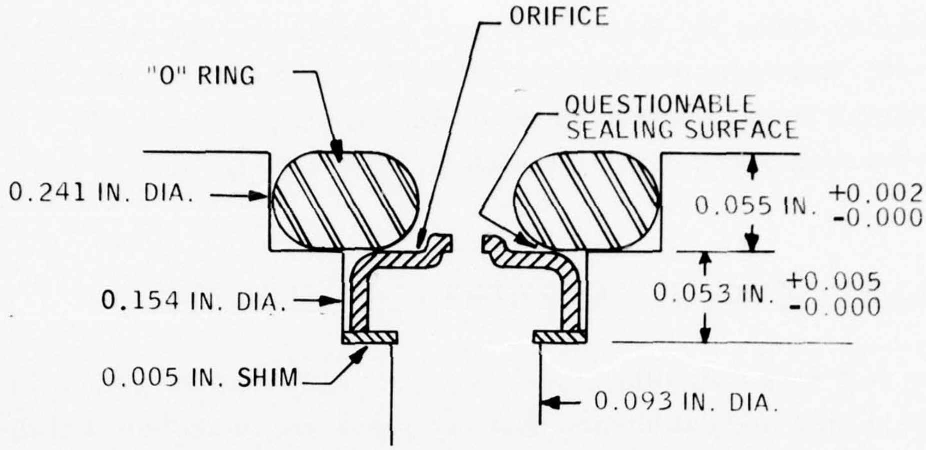


Figure 11. Sealing of Orifice Cup - Operational Suitability Design.

A completed controller was disassembled and cleaned to determine if contaminants had entered during the fabrication and assembly process. Three particles large enough to block a resistor were found (typical size was 0.020 inch in diameter). Use of ultrasonic cleaning on all assemblies was initiated.

Yaw axis controllers were proof pressure tested to 900 psi. At this pressure, excessive bending occurred on the manifolds. More and stronger bolts were used to prevent this deflection.

Conductive wax was not completely removed from one manifold and several amplifiers during the initial cleaning process. The obstructions were noted during component tests and system calibration. All manifolds and the affected amplifiers were recleaned. Improvement in the cleaning process is planned for future programs.

The viscosity of hydraulic oil changes with use in the test bench as well as in the aircraft. Because the viscosity of the hydraulic oil in the test bench was low, although still within specification limits, it was changed. When Ft. Rucker yaw axis controllers were retested with the new oil, their gain performance at 120°F was low on several units. Four systems were recalibrated to provide higher gain below 120°F to prevent the occurrence of this problem in the aircraft.

ROLL AXIS CONTROL SYSTEM FABRICATION AND TEST

Fourteen roll axis controllers were fabricated and tested. Flightworthiness test results and calibration data are presented in Section II of the Data Package. Roll axis controllers were calibrated at 120°F and checked at 180°F. A single flow control valve set at 0.7 GPM ± 10 percent is used for the two-axis OH-58 system. It is installed in the yaw axis controller.

Calibration of each yaw axis controller compensates for any error in the flow control valve; however, all roll axis controllers were calibrated using the same flow control valve with a flow of 0.643 GPM. When installed on the aircraft, most roll axis controllers will have a higher gain than that given in Section II of the Data Package because most flow control valves (in the yaw axis controllers) have a flow higher than 0.643 GPM. Null offset is another parameter that is sensitive to flow.

The major design change incorporated into the roll axis controller for operational suitability was that the size of the standoffs on both the upper and lower manifolds was reduced. These smaller standoffs, which use a 005 "O" ring rather than a 007 "O" ring as on the original roll axis controller, are used on both yaw and roll axes controllers because they are more consistent and improve performance. However, during proof pressure testing it was discovered that the spacer plate (Figure 8) had not been redesigned and the holes were sized for 007 "O" rings. Small spacer rings were then fabricated and placed in the oversize holes to reduce their effective diameter. Figure 12 shows a cross-sectional view of a typical junction between the upper and lower manifolds. One junction is required to have a 0.028-inch-diameter orifice, which is attached in the manner shown. A replaceable orifice cup cannot be used in this location because the height is insufficient to use the Figure 11 configuration and the standoff diameter is too small to use the Figure 13 configuration. These changes proved to be satisfactory.

Proof pressure testing also showed that the hold-down clamps were not strong enough to contain the rate sensor covers; therefore, a stronger hold-down plate was designed (Figure 8). Stainless steel bolts used for holding down the manifolds were replaced with high-strength bolts to obtain the 900-psi proof pressure capability.

The cause of a large, unexplained offset at the output of the high pass was determined to be the physical orientation of the bias resistors as shown in Figure 14. Because the flow through R7 impinged directly on R6, the recovered pressure at P1 is greater than at P2 even though R6 and R14 are equal. Figure 6 shows the location of these resistors in the circuit. This problem was solved by pressing a diverter plug into the lower manifold baseplate as shown in Figure 15 to prevent impingement of the stream from resistor R7 onto resistor R6.

Another bias circuit problem was uncovered while testing the system over a wide fluid temperature range. In the circuit shown in Figure 16, pressure P_1 usually equals P_2 and is lower than P_o. Under some temperature conditions, the pressure levels at P_1 and P_2 would increase such that they would become as large as P_o. In this case the pressure drop across R6 and R14 would be zero, and the resistance of R6 and R14 would be nearly zero. This would result in a short across the high

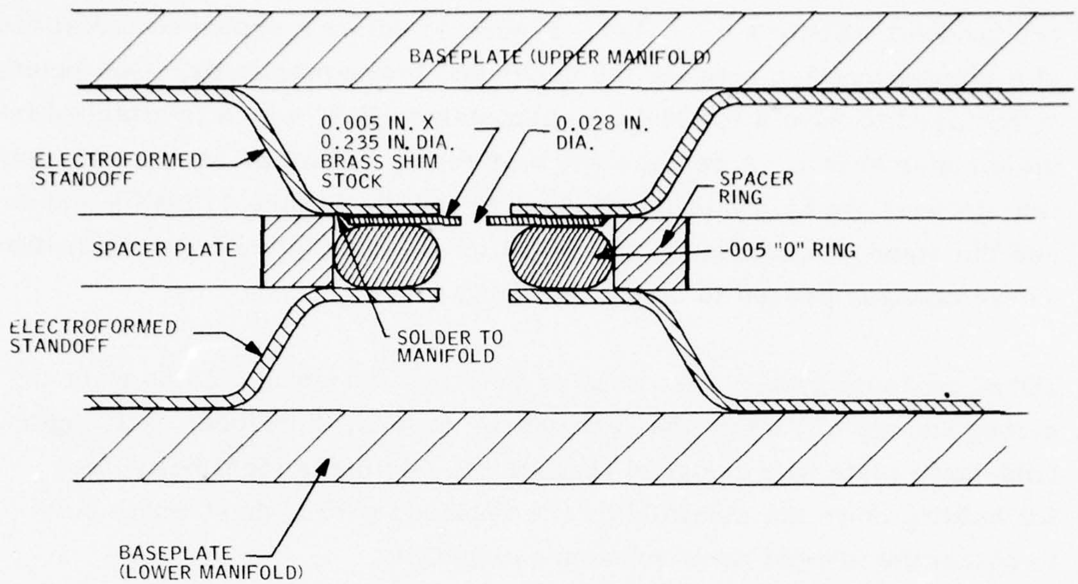


Figure 12. Cross Section of a Typical Junction Between Upper and Lower Manifolds.

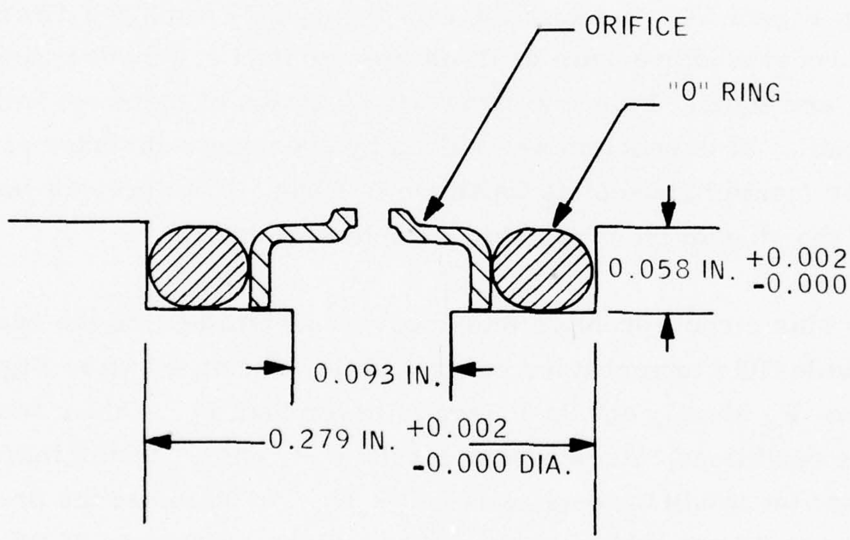


Figure 13. Sealing of Orifice Cup - Original Roll SAS.

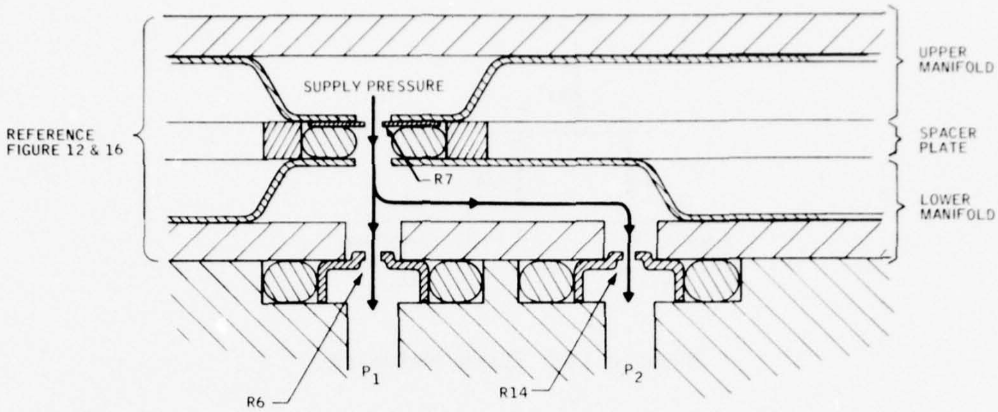


Figure 14. Original Bias Resistor Configuration.

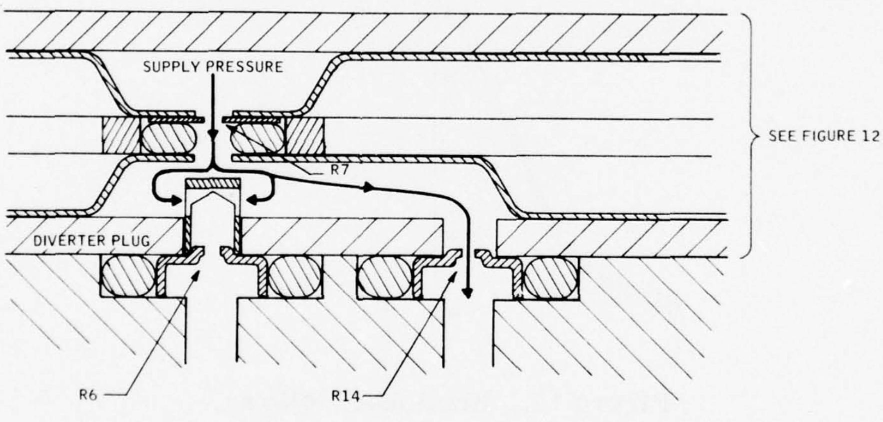


Figure 15. Bias Resistor Configuration with Diverter Plug.

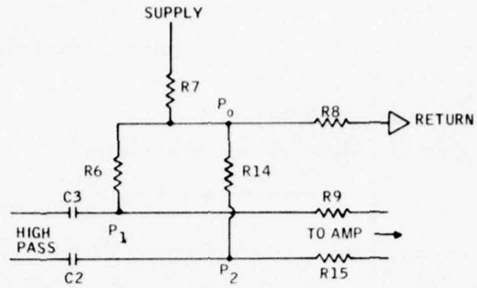


Figure 16. Bias Network.

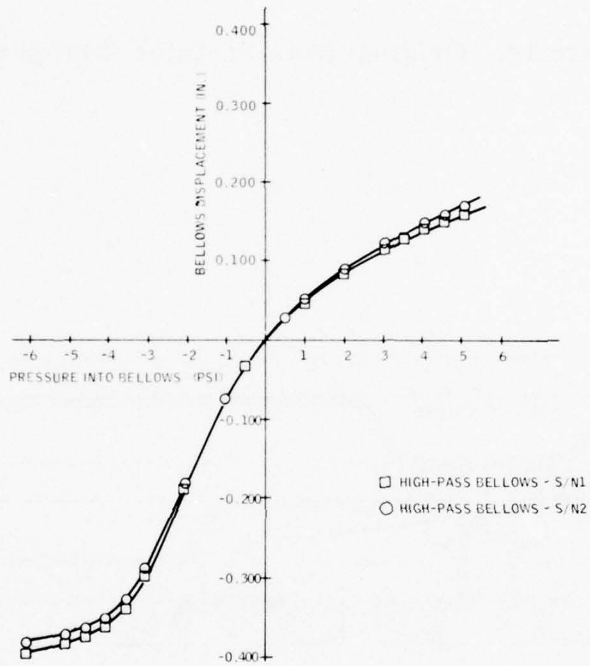


Figure 17. Nonlinear Bellows.

pass and very low system gain. The problem was solved by blocking resistor R8 and eliminating resistor R7, thereby ensuring a positive flow through bias resistors R6 and R14 at all times.

A nonlinear lag bellows that could change the lag time constant by a factor of three depending upon the amount of offset in the preamplifier presented another problem. This same bellows was tested on another program and was found to have the characteristic shown in Figure 17. Spring rate at 2 psid in compression was less than 10 psid per inch of deflection. This increases to 30 psid per inch at a pressure of 2 psid in extension. Nominal operating point for a lag is 0 psid (neither compression or extension); however, for a high pass the operating point can be biased to operate in the linear portion of the curve, which is about 2.5 psid in compression. A more expensive electroformed bellows with a linearity of about ± 5 percent was ordered for the lag circuit when the magnitude of the problem was realized.

SECTION III
INSTALLATION DESIGN

Two installation kits were designed. The KG1216AA01 is the yaw axis stability augmentation kit for the TH-57 aircraft, and the KG1217AA01 is the two-axis stability augmentation kit for the OH-58 aircraft. All parts necessary for installation of the appropriate HYSAS and a complete set of instructions were included with each kit. Each of the two installation facilities (Pensacola and Ft. Rucker) was provided with a UG2555AA01 test set that was specifically designed to measure the performance of the HYSAS installations.

SUBCONTRACT SUPPORT

A subcontract was negotiated with Bell Helicopter Company (Textron) covering design support, specific items of installation hardware, installation of the HYSAS kits, and restoration of the helicopters following the operational testing. Design support included a definition of the two airframes, a review of installation drawings, and on-site consultation during first-article proofing of each configuration.

Hydraulic Research (Textron) modified the configurations of their cyclic servoactuators to eliminate a cowling interference that was experienced on a previous program.

DRAFTING

More than fifty drawings were generated to define the installation of these HYSAS kits. Eight of these were complex installation layout drawings; most of the remainder were piece-part drawings of brackets, supports, stiffeners, flexible hydraulic hoses, hydraulic tubes, shims, etc.

TECHNICAL MANUALS

All HYSAS kits included a current installation manual. This manual tabulated a list of parts for each sub-kit, provided a step-by-step procedure for installing the components in each aircraft, and defined a ground test checkout procedure. Supplements to Army Maintenance Manual TM-55-1520-228-34 and Operator's Manual TM-55-1520-228-10 were written and copies of these supplements were included in each KG1217AA01 kit.

INSTALLATION CONFIGURATIONS

The configuration of the Army installation is very similar to that used in the previous OH-58 flight test programs. Existing cyclic control servoactuators were replaced with fluidic input servoactuators, and a directional servoactuator with a fluidic controller was added as shown in Figure 18.

Major roll axis components are the controller (Figure 9) and the servoactuators (Figure 10). A side view of the roll axis installation is shown in Figure 19, and a top view is shown in Figure 20.

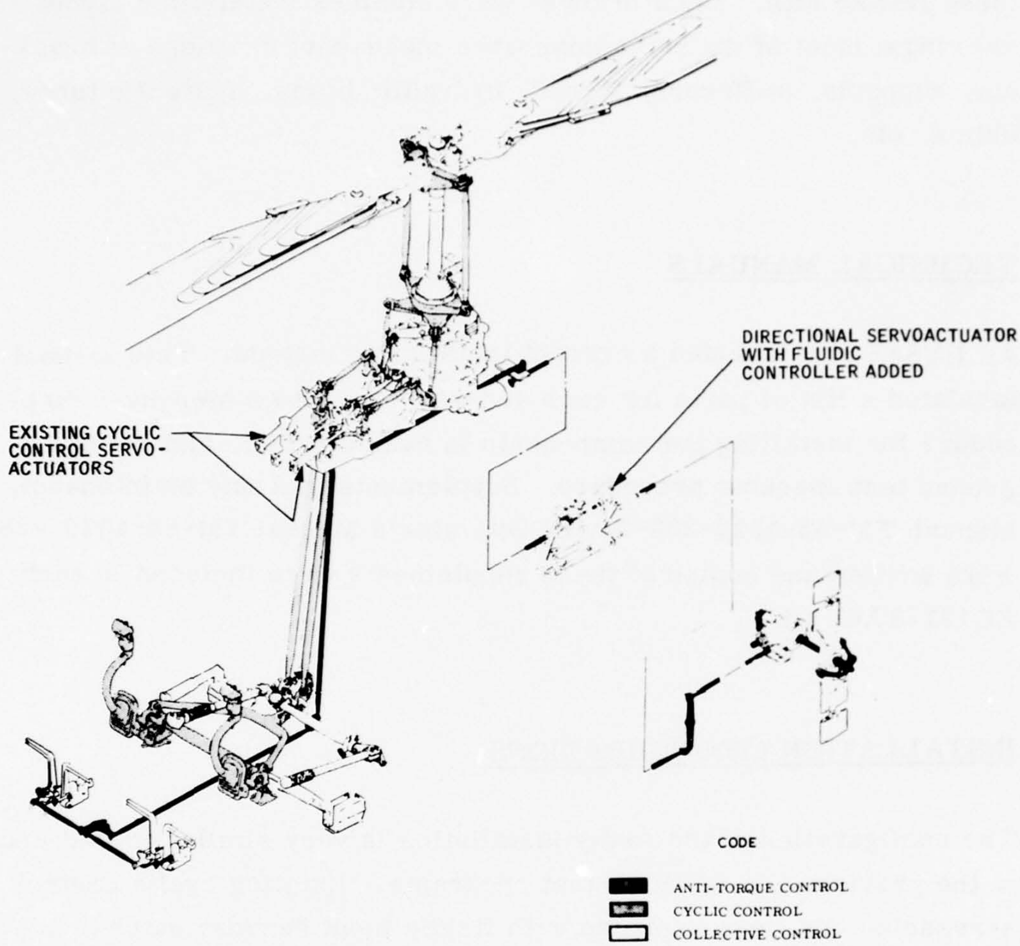


Figure 18. OH-58 Flight Controls.

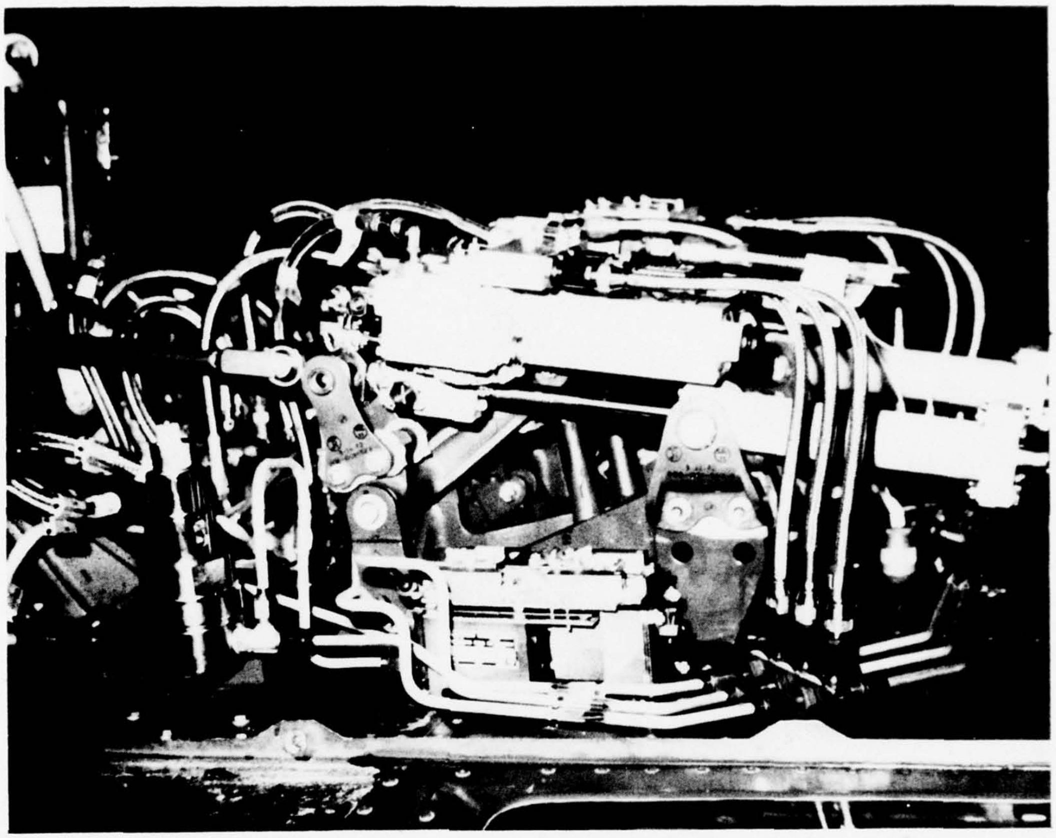


Figure 19. Roll Axis Assembly Installation - Side View.

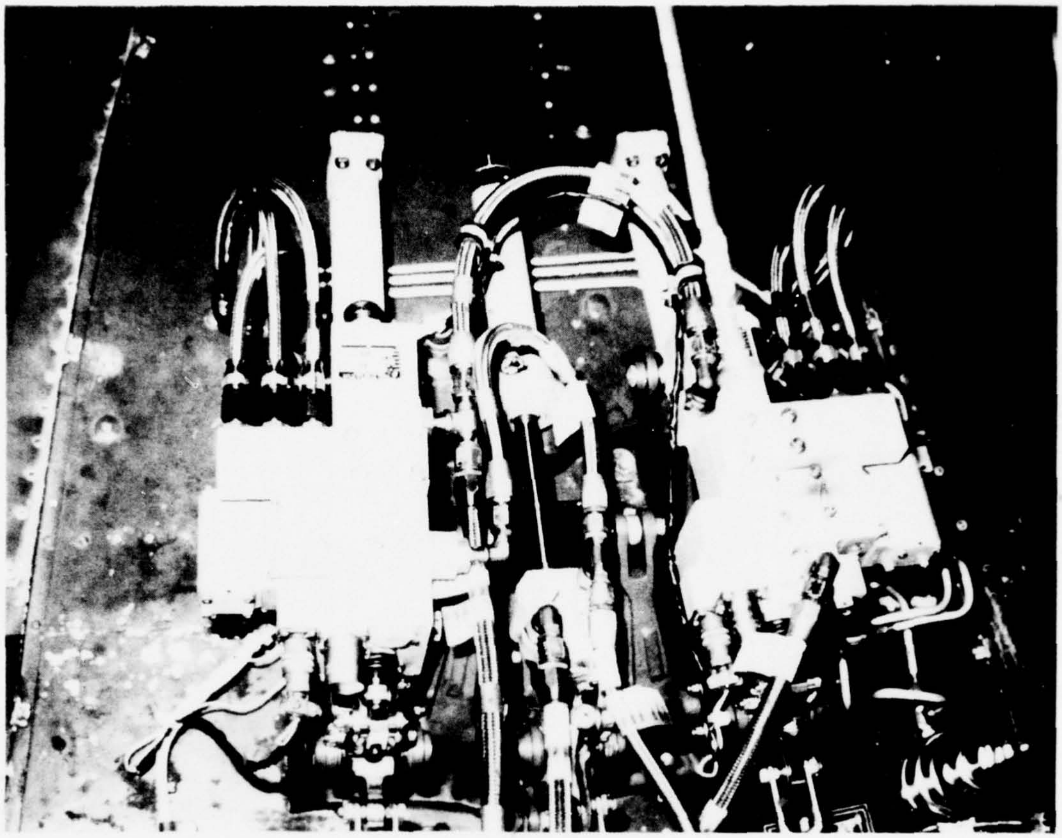


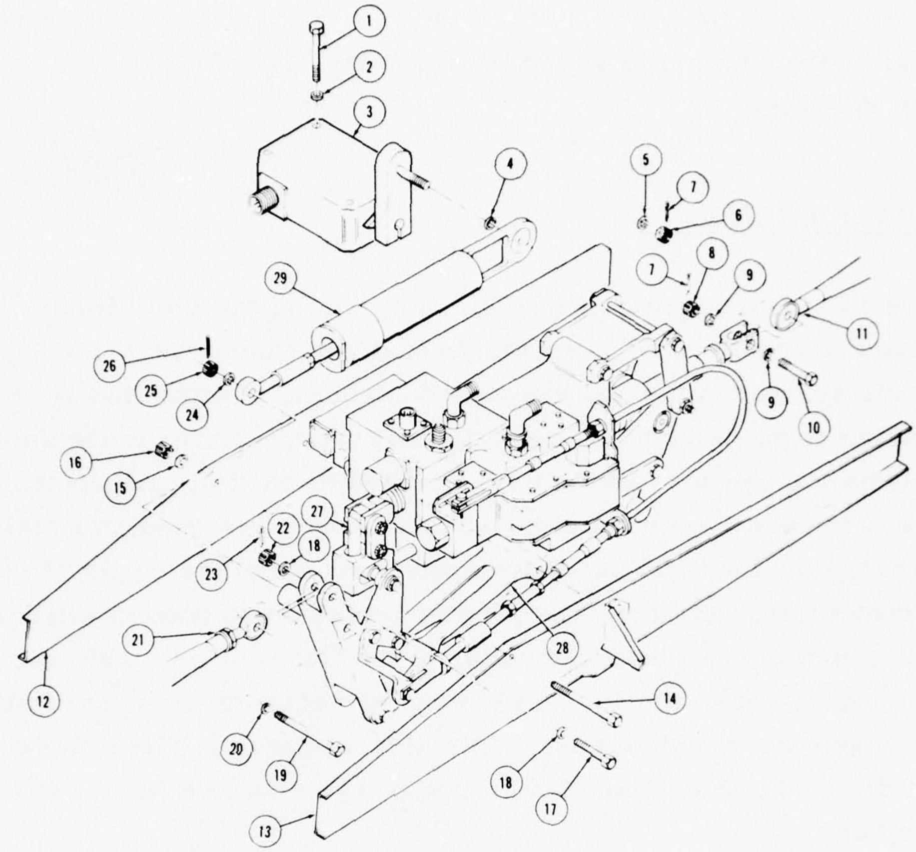
Figure 20. Roll Axis Assembly Installation - Top View.

Figure 21 shows the installation of the yaw axis system. This unit is located in the same area as the previous YG1105A01 HYSAS, which is shown in Figure 22.

HYDRAULIC CIRCUIT

Figure 23 is a schematic of the OH-58 hydraulic system. High-pressure hydraulic fluid is routed through the engine compartment to the yaw axis servoactuator and yaw axis controller. Output flow from the yaw axis servoactuator is routed to the system return, while the output flow from the yaw axis controller is routed to the roll axis controller, where it is used a second time. The back-pressure regulator maintains a pressure of about 100 psi above system return at the output of the roll axis controller. External plumbing is necessary to transmit hydraulic signals from the roll axis controller to the fluidic input cyclic servo-actuators, whereas similar connections are accomplished internally in the yaw axis servoactuator and controller assembly. The remaining hydraulic connections shown in Figure 23 are standard for the OH-58 helicopter.

The HYSAS configuration of the TH-57 hydraulic system is nearly the same as in the standard aircraft. The standard aircraft has a directional boost servoactuator with hydraulic supply and return lines; therefore, the only external plumbing change is connecting the controller return line to a back-pressure regulator as shown in Figure 24. The controller and servoactuator are connected internally.



1. AN14-22A, Bolt
2. AN960PD416, Washer
3. Honeywell p/n 10047861-101, Magnetic Brake
4. AN960PD416, Washer
5. Bell p/n 50Z16-8-5
6. MS17825-4, Nut
7. MS24665-151, Cotter Pin
8. MS17825-4, Nut
9. AN960PD416, Washer
10. AN174-20, Bolt
11. Honeywell p/n 10047490-101, Tube Assembly
12. Honeywell p/n 10047179-102, Support
13. Honeywell p/n 10047179-101, Support
14. AN4-41A, Bolt
15. AN960PD416, Washer
16. MS21042L4, Nut
17. AN174-13A, Bolt
18. AN960PD416, Washer
19. AN4-41, Bolt
20. AN960PD416, Washer
21. Honeywell p/n 10047494-101, Tube Assembly
22. MS17825-4, Nut
23. MS24665-151, Cotter Pin
24. Bell p/n 50Z12-9-2
25. MS17825-4, Nut
26. MS24665-151, Cotter Pin
27. Honeywell p/n 10047852-101, Yaw Servo-actuator and Rate Sensor Amplifier
28. Honeywell p/n 10047487-101, Anti-torque Cylinder Support
29. Honeywell p/n 10049191-101, Force Gradient

Figure 21. Yaw Axis Controller and Servoactuator Installation.

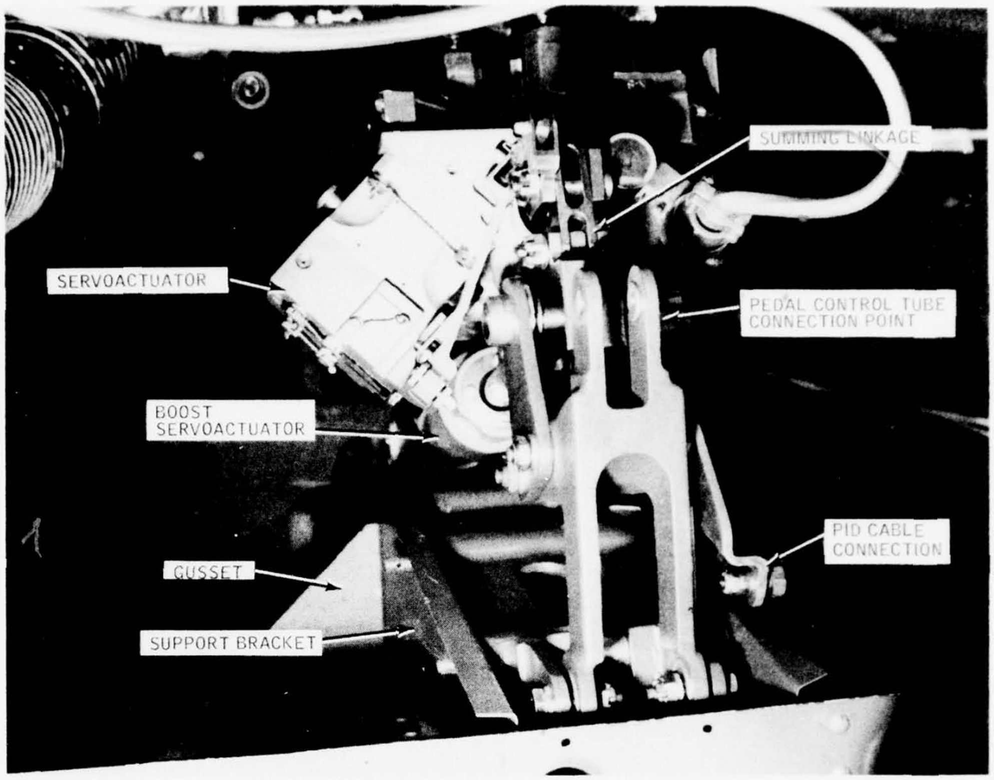
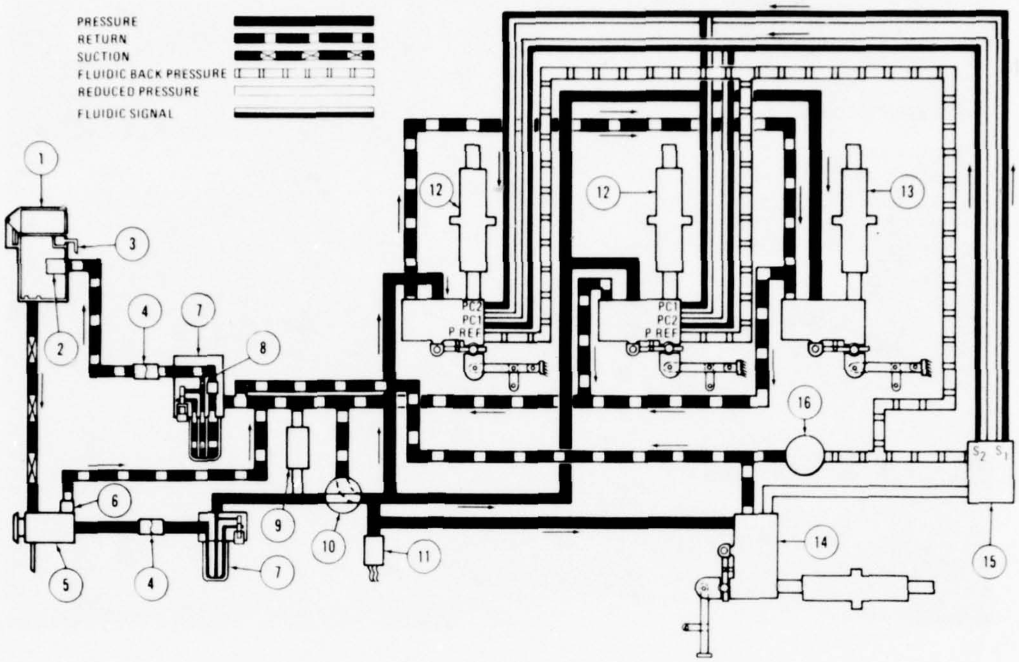


Figure 22. YG1105A01 HYSAS Installed.



1. Reservoir
2. Baffle
3. Scupper Drain
4. Quick Disconnects
5. Pump
6. Check Valve
7. Filter
8. Filter By-Pass Valve
9. Relief Valve
10. Solenoid Valve
11. Pressure Switch
12. Servoactuator, Cyclic (Roll)*
13. Servoactuator, Collective *
14. Servoactuator, Yaw and Rate Sensor Amplifier*
15. Roll Damper System*
16. Back Pressure Regulator*

*Honeywell parts are identified with an asterisk.

Figure 23. OH-58 Hydraulic System Schematic.

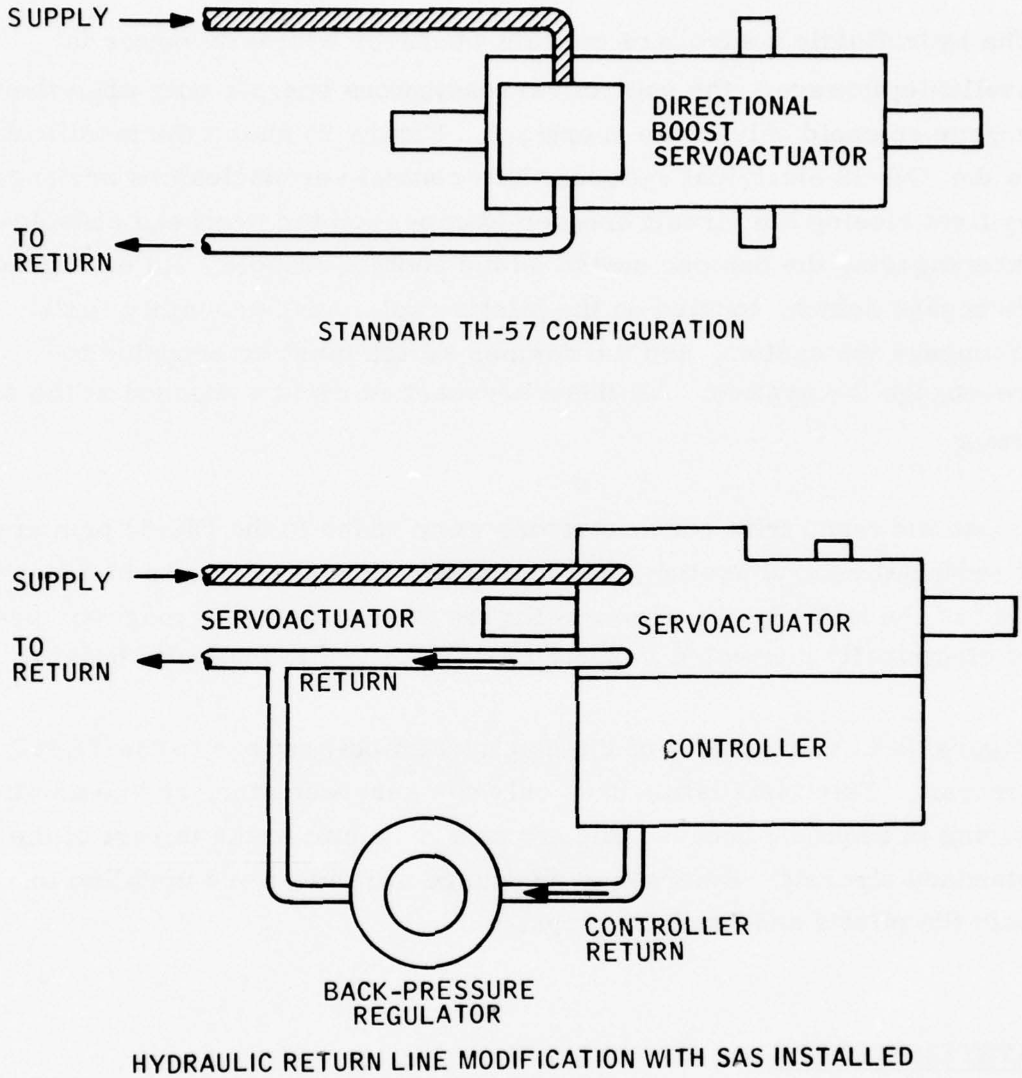


Figure 24. Standard TH-57 Hydraulic System Configuration and Modification with SAS Installed.

ELECTRICAL SYSTEM

The hydrofluidic controllers operate whenever hydraulic power is available; however, the control servoactuators operate only when their engage solenoid valves are energized. Figure 25 shows the modifications to the OH-58 electrical system. The control servoactuators are engaged by first closing the circuit breaker (damper) on the overhead console and then engaging the damper switch on the control console. An emergency disengage switch, located on the pilot's cyclic grip assembly, will disengage the system, and the damper switch must be recycled to re-engage the system. All three servoactuators are engaged at the same time.

Boost and force trim servoactuators were added to the OH-58 primary directional control system, and their operation was made to be independent of the HYSAS. As shown in Figure 26, the yaw axis magnetic brake is electrically connected in parallel with the cyclic magnetic brakes.

Figure 26 is a schematic of the electrical modifications to the TH-57 aircraft. This installation uses only one servoactuator, and no additional wiring is required because the yaw axis magnetic brake is part of the standard aircraft. Emergency disengage switches were installed in both the pilot's and copilot's grips.

SYSTEM TESTER

The performance of the newly installed systems was established using the UG2555AA01 test set and an appropriate strip chart recorder. Instructions for accomplishing this checkout are outlined in the

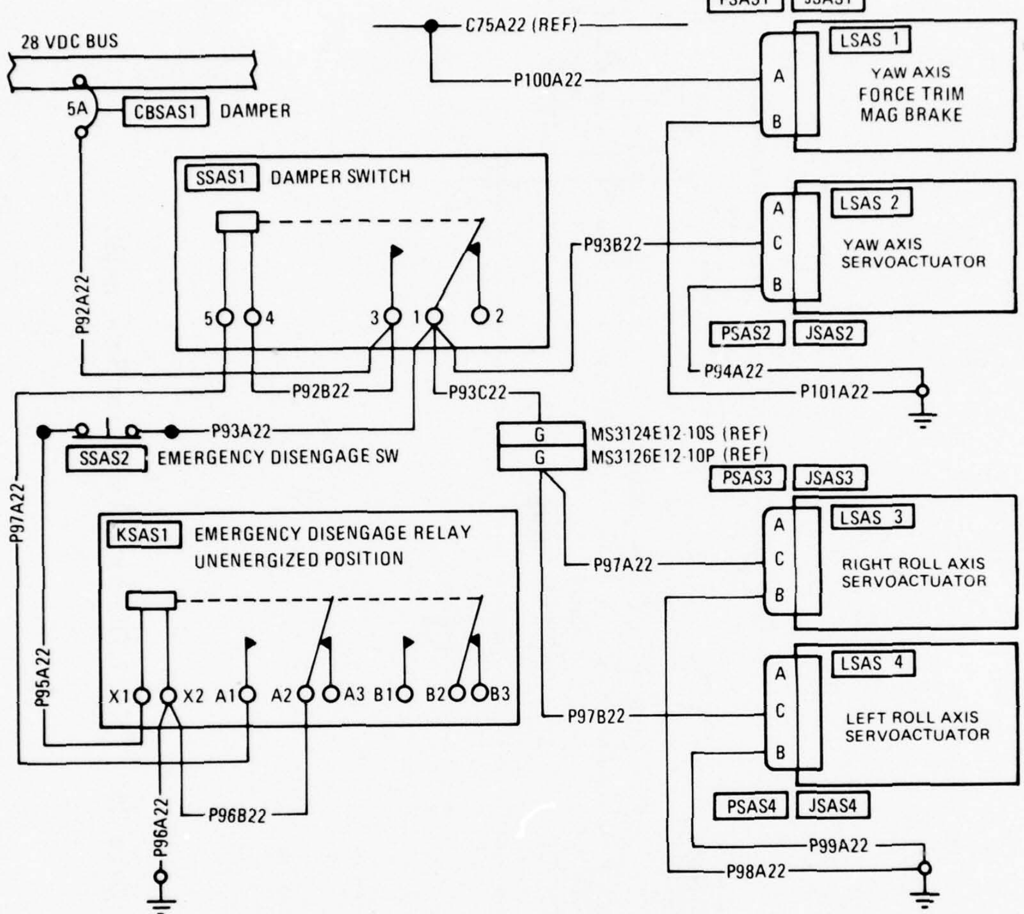


Figure 25. OH-58 Electrical System Schematic.

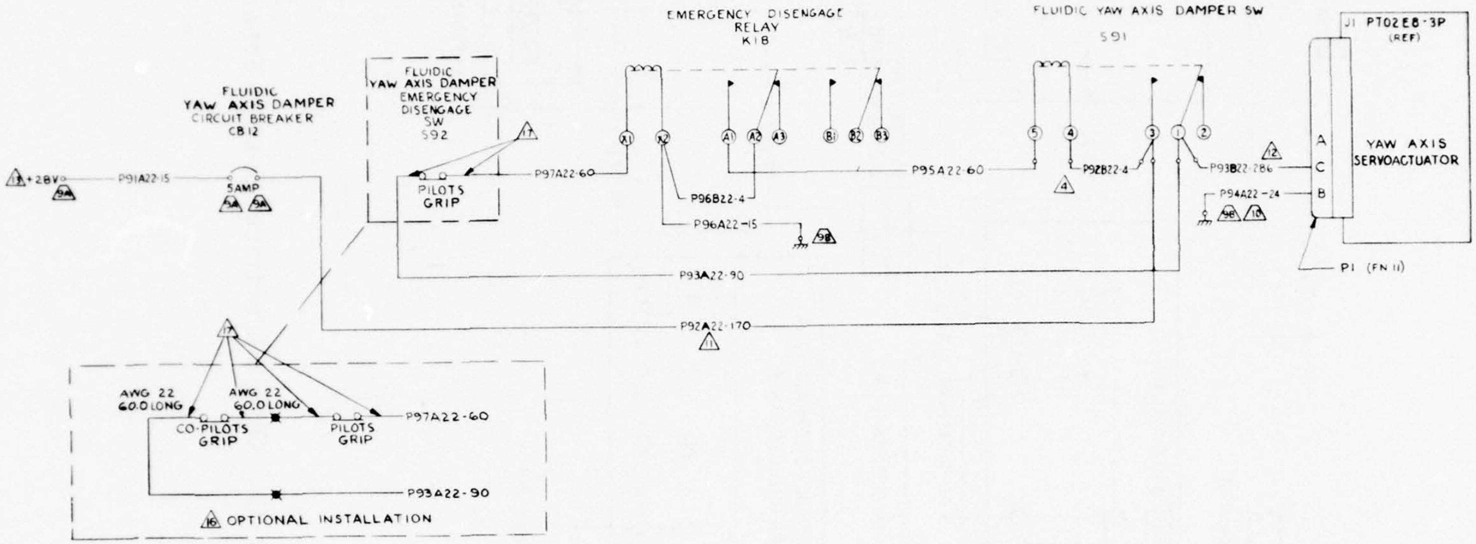


Figure 26. TH-57 Electrical System Schematic

installation manual. These tests were performed periodically during the 1-1/2 years of flight operation to determine if system performance was changing.

The tester is shown in Figure 27. Right and left pedal fixtures limit pedal travel so that test inputs of exactly 1 inch can be introduced. Yaw axis movable and yaw axis fixed transducer assemblies measure directional inputs at the tail rotor crosshead. Motion at this crosshead is the sum of the pedal input and yaw axis HYSAS input. Roll axis fixed and movable transducer assemblies are used only on the OH-58 helicopter.

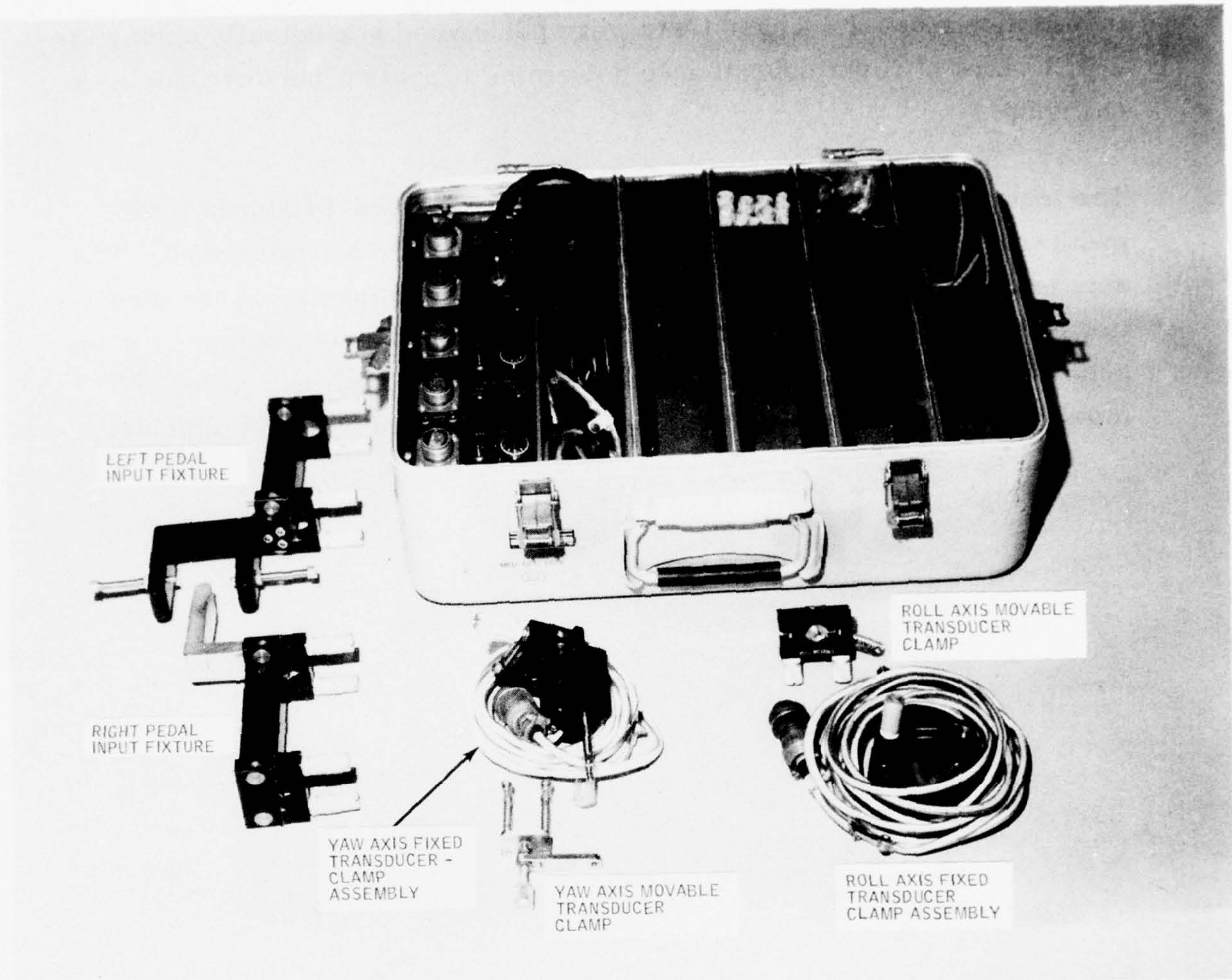


Figure 27. UG2555AA01 Test Set.

SECTION IV
SYSTEM INSTALLATION AND FIELD SUPPORT

Ten single-axis hydrofluidic stability augmentation systems (yaw) were installed in Navy TH-57 helicopters at Whiting Field near Pensacola, Florida. Twelve two-axis hydrofluidic stability augmentation systems (roll and yaw) were installed in Army OH-58 helicopters at Fort Rucker, Alabama. This section describes the field support activity during the installation and during the 1-1/2 years these systems were operating. The more significant malfunctions are described in Section III of the Data Package, and the circumstances of these malfunctions are described in detail in this section.

PENSACOLA INSTALLATION

First article proofing of the TH-57 HYSAS kit was conducted at Whiting Field, Pensacola, Florida, in October of 1974. Many discrepancies were uncovered in the area of the tail rotor servoactuator. Drawing changes, hardware modifications, and technical manual changes were incorporated as a result of this proofing.

Installation of the TH-57 systems started on March 3, 1975 at Whiting Field. Additional interference problems were discovered. One problem occurred when the magnetic brake was moved to the right-hand side of the ship. Of the many solutions proposed by the on-site team, the only satisfactory solution required a complete redesign of the magnetic brake support. Because redesign was required, the installation team investigated the possibility of moving the PID cable to the right-hand side and leaving the magnetic brake in its original position. New PID cable brackets were designed and fabricated on site. This solution was proved satisfactory and implemented. The new design eliminates the need for aircraft structural modification and reduces the installation time of each aircraft by 1 day.

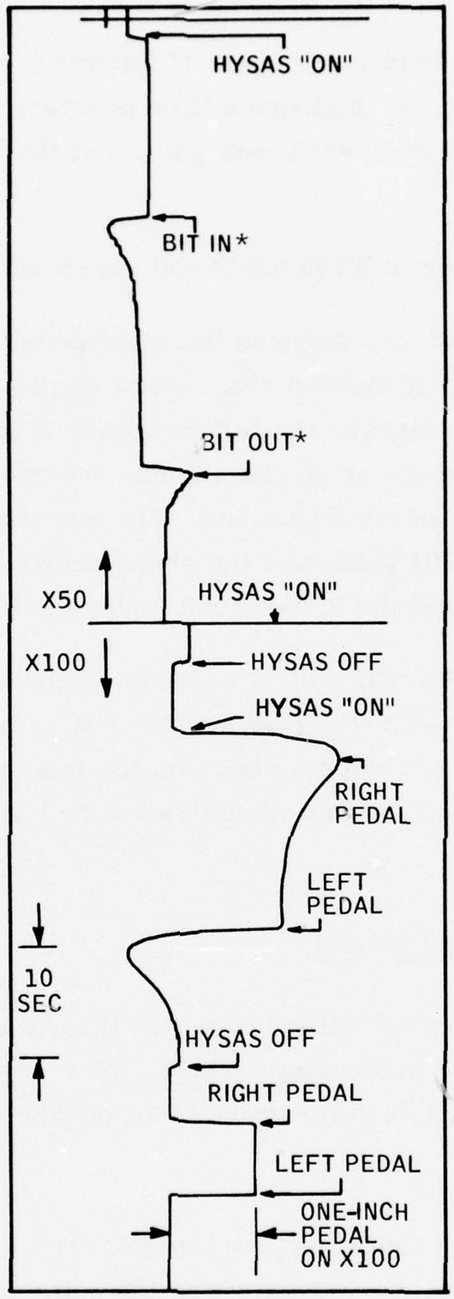
The flexible hydraulic hose configurations were also modified to minimize forces transmitted to the aircraft structure. The UG255 test set was checked out on the aircraft in accordance with the technical manual instructions. Initial test results were disappointing because the hydraulic cart oil temperature could not be increased above 90°F; the HYSAS was designed to operate over a temperature range from 130° to 180°F.

Installation was delayed for 5 weeks until the required changes could be implemented. Brackets were designed and fabricated, hoses were purchased in the new configurations, and manuals were revised. This delay also allowed the Navy to modify their hydraulic cart to operate at a higher oil temperature. Installation resumed on April 14. The hydraulic cart pump displacement adjustment was increased, allowing the oil to heat at a faster rate and the cart to stabilize at a higher oil temperature.

Each HYSAS was tested in a manner similar to that shown in Figure 28 before the aircraft was released for a test flight. The following is a summary of the test sequence used in generating this test data:

1. Connect test equipment per manual instructions and heat the HYSAS to at least 120°F oil temperature.

2. Turn on recorder, wait about 5 seconds, and turn on HYSAS. This defines the offset and engage transient.



* Each HYSAS has built-in test, BIT, a feature which introduces a pseudo rate signal into the rate sensor vortex chamber whenever BIT (or lock lever, null) is depressed.

Figure 28. TH-57 Strip Chart Recording of Yaw Axis Performance.

3. Depress BIT, hold it for about 15 seconds, and release. This will show polarity, high-pass time constant, approximate magnitude of the high-passed rate gain, and the amount of through-rate gain.

4. Adjust recorder to X100 scale and repeat on-off transients.

5. With the HYSAS on, depress the right pedal (it will move only 1 inch because of the test fixture and stops) and hold it for 15 seconds; then depress the left pedal and hold it for 15 seconds. This section of the strip chart curve shows the magnitude and characteristic of the PID input. The amount of overshoot is indicative of PID gain, and the shape shows the effects of the 1-second lag and the 2.5-second high pass in this circuit.

6. Turn the HYSAS off, wait 5 seconds, depress the right pedal for 5 seconds, and then depress the left pedal for 5 seconds. This last step provides a check on the tester and recorder calibration, as this step is equivalent to 1 inch of pedal.

FORT RUCKER INSTALLATION

First-article proofing of the OH-58 two-axis HYSAS kit at Fort Rucker, Alabama,was completed in January of 1975. Nearly 40 minor discrepancies ranging from tubing bend locations to typographical errors in parts lists were found.

Design changes were incorporated, and installation was started at the end of May 1975. Testing of the yaw axis was the same as shown in Figure 28. Roll axis test data is shown in Figure 29. Electrical transducers are mounted on each cyclic servoactuator and their output is recorded on a strip chart recorder. Engage transients show the magnitude of the offset, and by comparing the outputs of both cyclic servoactuators, it can be

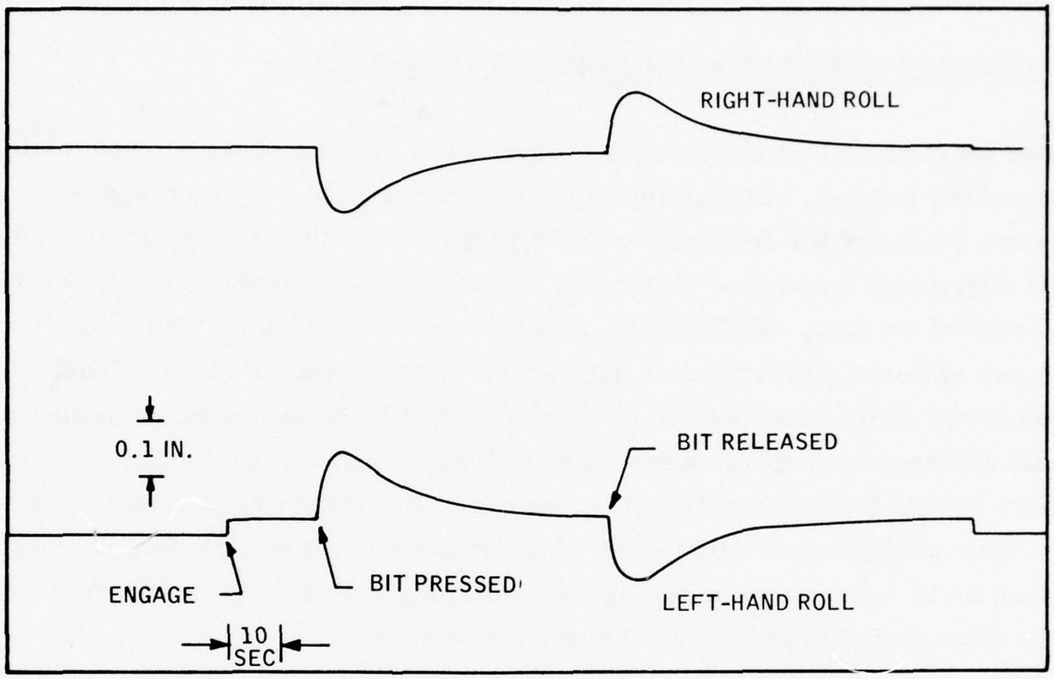


Figure 29. OH-58 Strip Chart Recording of Roll Axis Performance.

determined if the offset is in the controller or in one of the servo-actuators. Depressing BIT and releasing it about 30 seconds later provides traces that indicate the relative gain and dynamics of the roll axis system.

SERVOACTUATOR SUMMING LINKAGE PROBLEM

The most prevalent problem in the field was binding of the servoactuator summing linkage. During installation at Pensacola, it was discovered that a tendency for feedback into the pedals from the servoactuator could be eliminated by proper shimming and by adjusting pedal friction to the specified amount. Malfunction reports were not written at this time because shimming is a normal part of the installation. Pedal feedback occurred again in some TH-57 aircraft after installation was completed and malfunction reports were written (see Honeywell Malfunction Report (HMR) B02010 and B02011); however, the problem was attributed to poor shimming or alignment. Manipulations of the summing linkage, such as those occurring during the shimming process, probably freed the linkage and appeared to correct the problem.

During installation at Lowe Field in Fort Rucker, the problem of force feedback into the pedals occurred again and could not be corrected by shimming or adjustment (see HMR B02014). Yaw axis controller S/N 16 was removed from the aircraft and sent to Honeywell to determine if the problem could be duplicated in the laboratory.

The laboratory acceptance test fixture was modified to include the aircraft antitorque control lever (Item 9 in Figure 30) so that the magnitude of the effective pedal forces could be measured. Figure 31 is a photograph of the force-inducing summing linkage and Figure 32 is a detailed sketch. Tests demonstrated that excessive friction on the

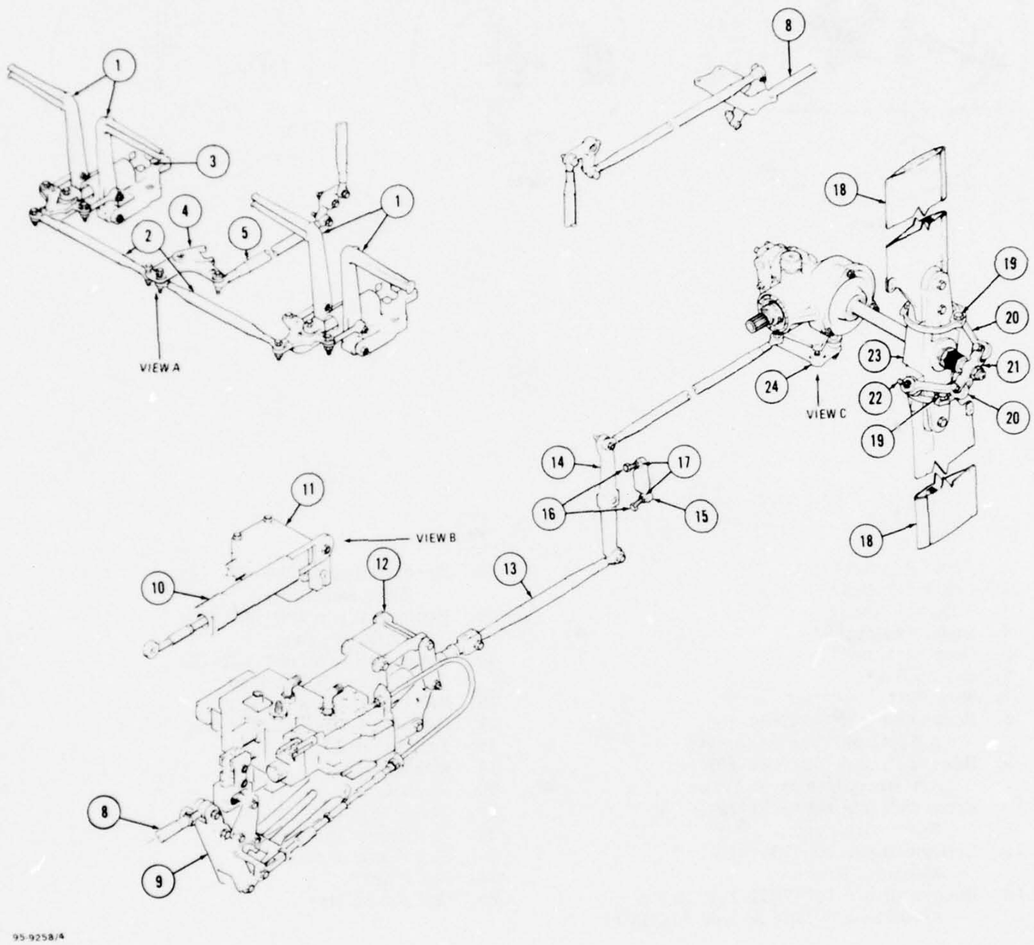
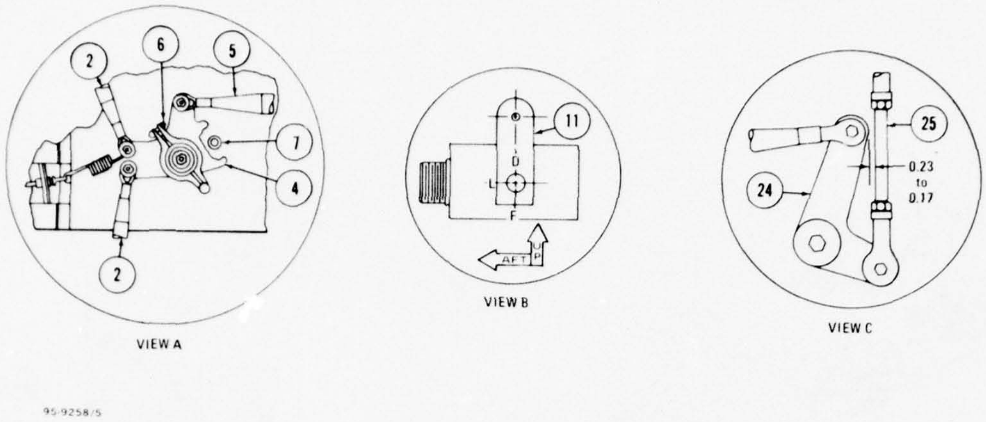


Figure 30. OH-58 Antitorque Control System.



1. Pedal Assembly*
2. Control Tubes*
3. Adjuster Knob*
4. Pedal Bellcrank*
5. Control Tube*
6. Clamp Nut*
7. Stop Pin*
8. Honeywell p/n 10047494-101, Adjustable Tube Assembly
9. Honeywell p/n 10047486-101, Anti-torque Control Lever
10. Honeywell p/n 10049191-101, Force Gradient
11. Honeywell p/n 10047861-101, Magnetic Brake
12. Honeywell p/n 10047852-101, Servo Actuator and Rate Sensor Amplifier
13. Honeywell p/n 10047490-101, Tube Assembly
14. Honeywell p/n 10047491-101, Walking Beam
15. Honeywell p/n 10047492-101, Walking Beam Stop
16. NAS428-4-12, Stop Bolt
17. NAS509-4, Drilled Jam Nut
18. Tail Rotor Blade*
19. Washer(s)*
20. Pitch Link*
21. Tail Rotor Crosshead*
22. Tail Rotor Pitch Horn*
23. Tail Rotor Yoke*
24. Bellcrank*
25. Rod Assembly*

*Existing Bell parts are denoted with an asterisk

Figure 30. OH-58 Antitorque Control System (Concluded).

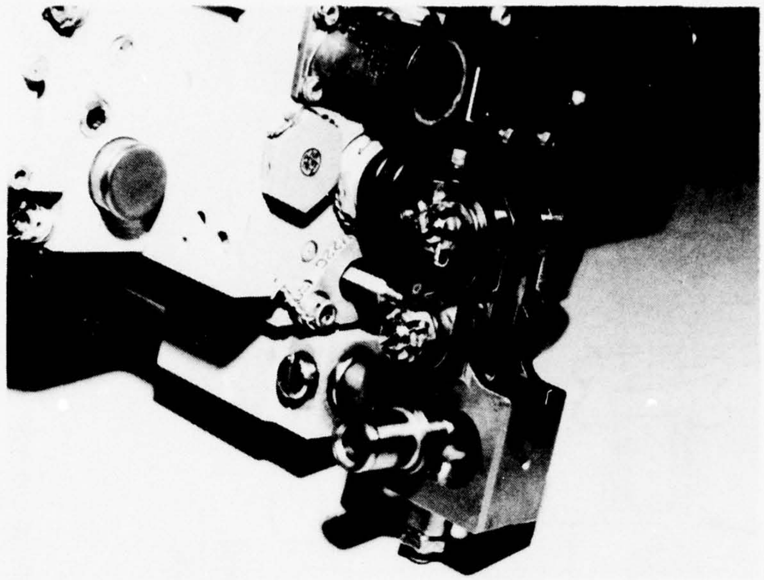


Figure 31. Servoactuator Summing Linkage - Photograph.

upper bolt caused the control servoactuator output to "kick" back into the pedals rather than move the servoactuator pilot valve. Experiments showed that proper shimming in the area of the upper bolt could prevent friction-producing misalignments. Inspection of the unit also showed that there was some wear between the lower spacer and its slot in the rod end assembly.

Review of the linkage design included a review of the results of the described tests, results of previous flight tests on a very similar design, and data on the original design. It was concluded that the force feedback problem could be eliminated by incorporating the changes outlined in Figure 33. The upper bolt was modified to accept an aluminum bronze bushing, thereby providing a good bearing surface for the center link. The 15-5PH sleeve was used to hold the bushing in place and to provide proper spacing for the upper bolt linkages. Shims were to be used to maintain proper alignment of the upper bolt linkage. The lower spacer was

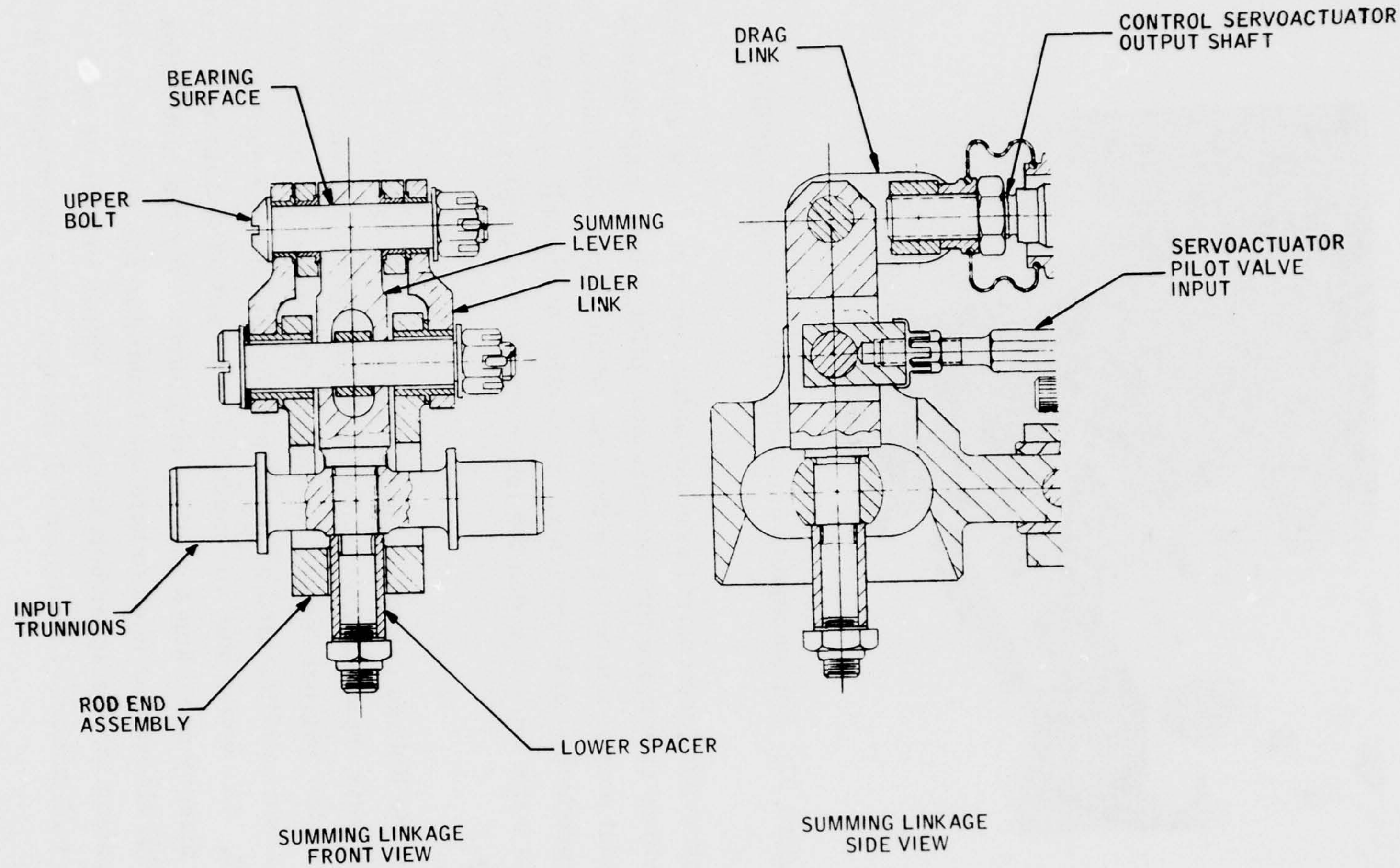


Figure 32. Servoactuator Summing Linkage - Sketch.

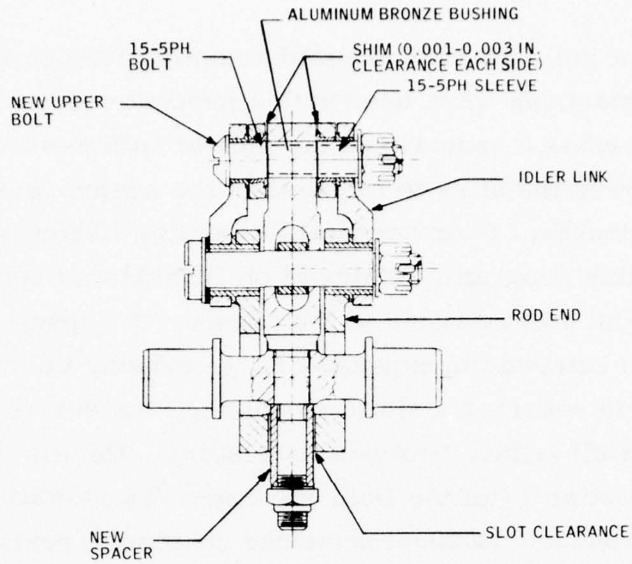


Figure 33. Modified Summing Linkage.

replaced with a smaller diameter unit to prevent contact. It was anticipated that this retrofit would solve the binding problem; however, it was also recognized that this was an interim configuration and that a complete redesign would be required on future builds of similar hardware. A stress analysis on the revised design showed that the new bolt design was acceptable under all static, dynamic, and ultimate load conditions. All summing linkage in the field was modified to incorporate the described changes in August 1975.

Summing linkage friction is most noticeable on the roll axis servoactuators of the OH-58 helicopter. Some summing linkage friction can be tolerated if the flight control stick minimum friction is adjusted to its prescribed limits of 1±0.5 lb (Ref. TM55-1520-228-34)[5]; however, it was policy at Lowe Field to adjust this friction to zero. Pilots strongly objected when on several aircraft this flight control stick friction was adjusted to the specification limits, contending that this friction makes control of the aircraft more difficult.

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5. DS and GS Maintenance Manual, Army Model OH-58 Helicopters, Headquarters, Department of the Army, TM55-1520-228-34, Nov. 1972.

It appears as if the field retrofit reduced summing linkage friction to where it was undetectable when used with a properly adjusted linkage. HMR B02030 describes a case where the lack of sufficient flight control stick friction allowed the stick to move when the system was engaged in a "hands off" maneuver. Four additional summing linkage malfunctions occurred during this program. Malfunction B02033 was considered to be an isolated case and was returned to the vendor. It appeared that some contamination had entered the exposed linkage causing binding. When malfunction B02039 reported a similar problem, the servoactuator was sent to the Honeywell failure analysis laboratory. Details of this analysis are reported in Section IV of the Data Package. Two additional linkage malfunctions (B02047 and B02055) occurred during the remainder of the program.

Servoactuator summing linkage friction was checked on eight OH-58 aircraft on 2-3 August 1976. Friction on the lower bolt was measured with a torque wrench. It was found that two servoactuators out of 24 had excessive friction. One inch-pound or less is normal, but the left-hand roll axis servoactuator (S/N 001) on aircraft 774 had a torque of over 1.5 inch-pound. The left-hand roll axis servoactuator (S/N 004) on aircraft 775 had a very large 4-inch-pound torque. Three other bolts gave an audible squeak when rotated, but their torque was less than 1 inch-pound. The subject bolts were each packaged separately with their data as summarized below and sent to the servoactuator vendor.

Servoactuator	Aircraft No.	Total Flight Hours	Reason for Removal
Tail Rotor - 5000 S/N 020	352	352.2	Squeak when rotated
Left-Hand Roll Axis - 5140 S/N 001	774	200.6	Excessive torque, 1.5 in.-lb
Left-Hand Roll Axis - 5140 S/N 004	775	296.2	Excessive torque, 4 in.-lb
Left-Hand Roll Axis - 5140 S/N 010	160	107.9	Squeak
Right-Hand Roll Axis - 5150 S/N 003	352	343.4	Squeak

There was a concern that the servoactuator summing linkage problem might become more severe. Vendor investigations showed that most of the observed deposits could be dissolved off and minor discoloration could easily be removed with a light application of crocus cloth.

An extensive summing linkage redesign will be required if this or similar servoactuators are used in the future. The following factors should be considered when evaluating linkage designs:

- The pedals and stick are cycled frequently with the hydraulic boost off. This results in large forces on the linkage which can cause excessive wear or damage.
- It should be determined which surfaces are bearing surfaces, and the forces on these bearings should be calculated under worst-case conditions. Some surfaces such as the lower bolt are a bearing surface only when the boost is off.
- When a linkage design uses a large number of pieces, the potential for jamming as a result of slight misalignments increases.
- Linkages should be capable of tolerating moderate amounts of contamination and/or should be protected.

LEAKAGE

Leakage problems were encountered as frequently as summing linkage problems but were easier to detect. The three major leakage problem areas were the PID "O" rings, the BIT "O" ring, and the flow control valve "O" ring. Leakage resulting from contamination or from an electroforming problem will be discussed under those categories.

PID leakage was the demonstrated or suspected cause of leakage in seven malfunctions: B02012, B02022, B02023, B02031, B02044, B02049, and B02052. A drawing of the PID spool and sleeve is designated as Section C-C in Figure 2, and the spool can also be seen in Figure 3. The spool seal design is identical to that designed on Contract DAAJ02-72-C-0051 (Reference 1). It proved to be satisfactory in laboratory tests and in flight tests. This design uses substantially less "O" ring compression than that of similar standard applications to reduce friction and to prevent damage to the "O" ring during assembly. If the compression were large, the "O" ring would extrude into the metering slot during assembly and this material would be sheared off as the "O" ring moved past the end of the slot. This would not only damage the "O" ring but it would also introduce contamination. A complete redesign will be required in future applications, and it must have the following features if a spool and sleeve configuration is selected.

- Standard "O" ring compression will be used.
- The "O" ring will not be subjected to damage during assembly.
- The mechanism will be compatible with the higher friction levels associated with the greater compression.

The PID design was marginal; however, many of the installations worked satisfactorily throughout the 1-1/2-year program. Those that leaked did so only when the aircraft was parked. Internal pressure under this condition was equal to a head of several feet of oil, which is insufficient to seat the "O" ring. During laboratory testing, the level of the reservoir was below that of the PID valve, thus preventing external leakage; during operation or flight, the pressure was very high,thereby seating the "O" ring. It appears that the "O" ring became unseated when the aircraft was parked and the pedals were moved with the hydraulic system off.

An interim corrective action consisted of using a larger 006 "O" ring in place of a standard 005 "O" ring to slightly increase compression. This corrective action was incorporated in all Pensacola units in October 1975. OH-58 yaw axis controllers received this modification whenever a problem occurred or whenever they were returned to Minneapolis for another problem. The larger "O" ring reduced the problem but some seepage was observed on units incorporating the modification.

BIT leakage was found during installation but was never experienced after the aircraft had completed its initial ground check. The BIT assembly is defined as Section D-D in Figure 2. The null adjust pin (No. 10 in Figure 2) and the "O" ring are retained by the locking sleeve (No. 11). This sleeve tends to work loose when BIT is depressed and released repeatedly (i. e., when the null adjust pin is rotated repeatedly). To correct the problem, this sleeve was permanently "staked" using a center punch on all units. This "staking" can be seen in Figure 34. All of the OH-58 units and some of the TH-57 units received this modification before they were shipped. The remaining TH-57 units were modified on site in Pensacola.

Flow control valve leakage resulted because the "O" ring entrance chamfer was machined too deep in the controller housing. "O" ring compression was sufficient on most units, preventing any leakage; however, some slight leakage was experienced on a number of other units. Figure 35 is a sketch of the flow control valve installation. An additional "O" ring was incorporated in the location shown in Figure 35 on Pensacola controllers during October of 1975. OH-58 units received this corrective action only when they were returned to Minneapolis or when they showed signs of leakage. Flow control valve leakage was the subject of HMRs B02009 and B02028.

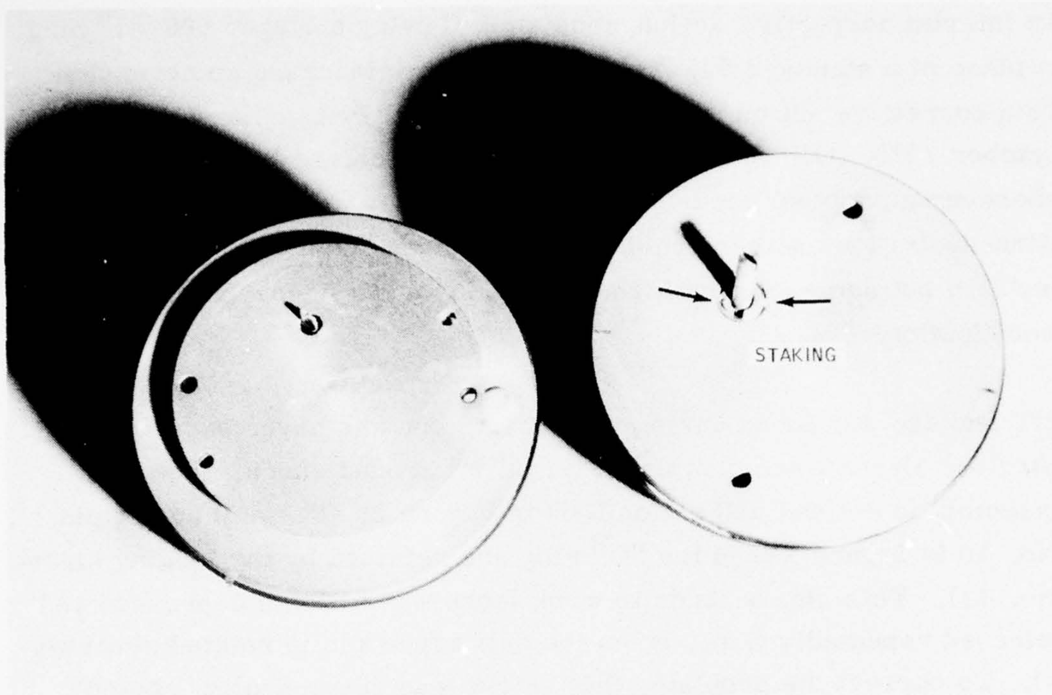


Figure 34. Staking of BIT Locking Sleeve.

MISHANDLING

Most of the mishandling problems occurred during the shipment of yaw axis controllers mounted on their servoactuators. Shearing off of the PID bracket screws, Figure 36, was the most common occurrence and is reported in HMRs B02003, B02006 and B02013. This servoactuator assembly is relatively heavy and subject to damage during packing, shipment, and unpacking. The exact point where and how the malfunction occurred has not been determined. Improved packaging greatly reduced the mechanical damage experienced during shipment; however, some servoactuator assemblies are still damaged when they are returned from the field.

Servoactuator null, HMRs B02001 and B02025, is another example of probable mishandling. A sharp blow to the servovalve will cause it to move on its mounting, resulting in a null offset. This relatively heavy tail rotor servoactuator assembly is installed in tight quarters and is

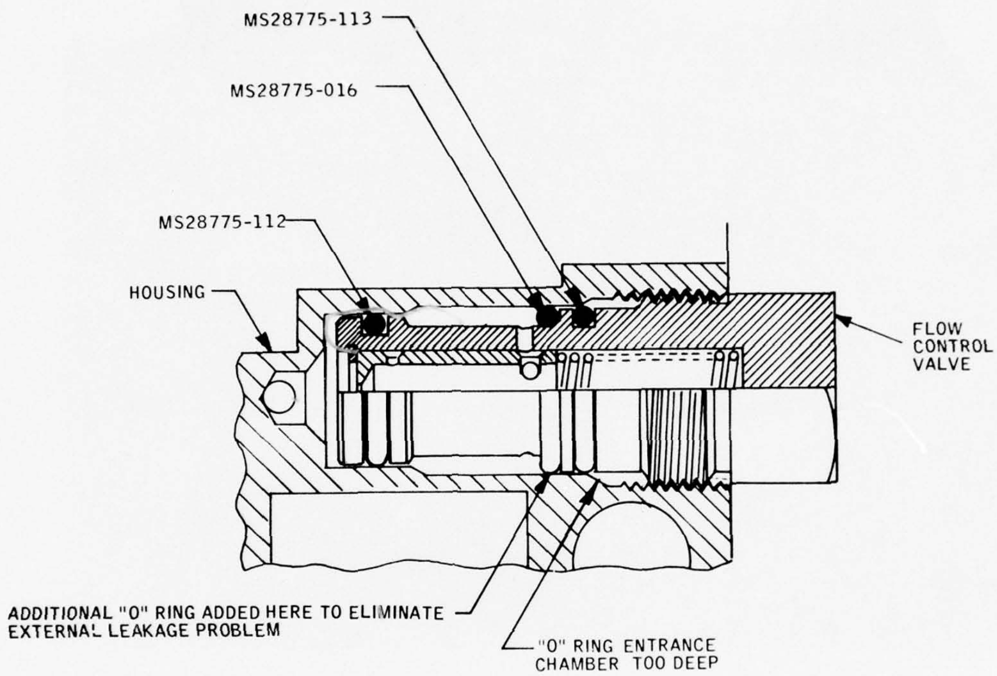


Figure 35. Flow Control Valve Installation.

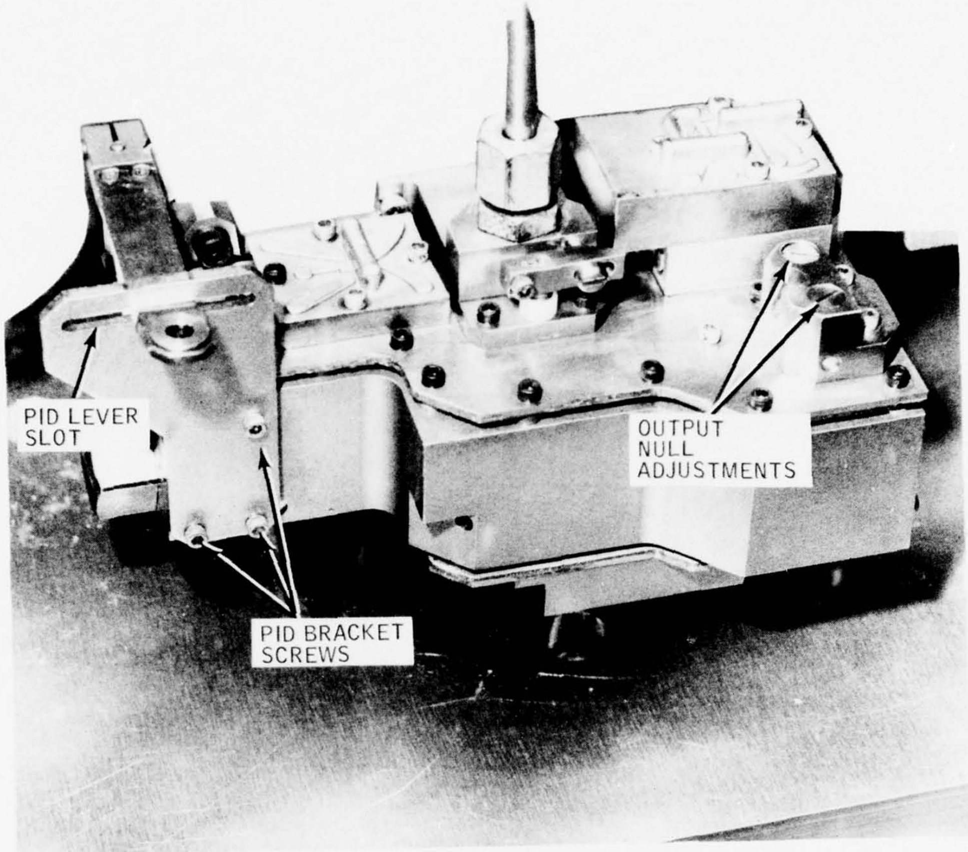


Figure 36. Yaw Axis Controller.

sometimes manipulated quite forcefully to obtain required alignment during installation. Both the PID bracket and the servovalve can be easily redesigned to be more tolerant of abuse. In production, the packaging would also be redesigned to prevent shipping damage.

CONTAMINATION

Incomplete removal of the conductive wax after electroforming appears to be the cause of malfunctions B02024 and B02040. The cleaning methods used on this program were demonstrated to be unsatisfactory; therefore, an improved technique using hot solvent under high pressure has been developed. It should be recognized that each new design will have its unique cleaning requirements, and some development will be required to ensure complete wax removal.

Contamination entering the system during assembly or test appears to be the cause of the leakage reported in HMRs B02008 and B02048. Laminar flow benches are now being proposed for fluidic production programs to minimize the entrance of contaminants during assembly.

FIELD MAINTENANCE BY MILITARY PERSONNEL

Both Army and Navy maintenance men were proficient at removing and replacing the fluidic systems. However, because not all field maintenance men read blueprints correctly, mistakes such as incorrect system installation, reported in HMR B02034, occurred. The design is such that an improperly phased connection looks "better" than when properly phased. Use of different line sizes would prevent this problem; however, this is not always practical. As a minimum, a production design should appear neat and organized when the lines are properly phased and should have the appearance of being crossed or mixed up when improperly phased.

One objective of the program was to obtain recordings of HYSAS performance on each aircraft every few months; however, only a limited amount of data was obtained during the program.

Internal adjustments on the Navy hydraulic cart were set up to limit maximum output pressure to about 650 psig even if the operator made a serious error. However, since this cart was oversized by several orders of magnitude, it was difficult to heat the fluid to the desired temperature of 120°F or greater. Honeywell worked with the Navy to change some internal adjustments which resulted in satisfactory operating temperatures (after a 45-minute warm-up period), but these adjustments were returned to their original settings when the hydraulic cart was sent in for maintenance. Some of the Navy data is misleading because of the low hydraulic oil temperature.

Army hydraulic carts were also large, but they could be adjusted to heat up or cool down within a few minutes time. These carts are very complex, and few people are capable of operating them. Malfunctions B02046 and B02056 are examples of overpressurization because of cart malfunction and/or operator error. The fluidic system can be maintained and replaced without the use of a hydraulic cart.

ADJUSTMENTS

PID null is adjusted during calibration by centering the lever in the slot and tightening the screw to clamp the PID lever clevis to the vertical shaft. These components are shown in Figure 36. Malfunction B02045 resulted due to slippage of the shaft in this clevis. This same problem also occurred on another program and is briefly discussed in

Reference 6. The solution was to extend the clevis slot, allowing better clamping action. This modification was not incorporated into the operational suitability units as they were already in the field when the solution was demonstrated. A complete redesign of PID hardware with positive locking will be a requirement on any future application.

Slippage of an output null adjustment (Figure 36) is the suspected cause of malfunction B02053. This adjustment is secured by friction, and a rubber base adhesive is applied after controller calibration is completed. Positive locking means will be used in future applications.

LEAKAGE DUE TO ELECTROFORMING PROCESS

During the electroforming process, the current density is much higher on the outside corners of the manifold plate resulting in a "flash like" buildup where the manifold plate joins the plating rack. A stackup of tolerances between this manifold and a mounting bracket caused the manifold to seat improperly due to this excessive nickel. This interference was so slight that it was not noticed on initial calibration or when it was returned to Minneapolis for malfunction B02029. After a failed "O" ring was replaced, the unit was proof pressure tested and returned to the field. Leakage occurred again,

[6] Walter Posingies, Production Suitability of an Electroform Conductive Wax Process for the Manufacture of Fluidic Systems, Phase II, Government and Aeronautical Products Div., Honeywell Inc., USAAMRDL-TR-76-42, Eustis Directorate, U. S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia, Jan. 1977, AD035173.

and the problem as reported in B02035 was discovered in the field. The present electroforming process specification requires the use of current robbers to obtain a more even current distribution to eliminate the large buildup of nickel on the edges of manifold plates.

SECTION V
RELIABILITY AND MAINTAINABILITY

HYSAS MEASURED AND PREDICTED RELIABILITY

During the HYSAS Operational Suitability Demonstration Program, 40 hydrofluidic stability augmentation systems (HYSAS) accumulated a total of 15, 950 flight hours while performing under actual helicopter operating conditions. Honeywell's Failure Reporting, Analysis and Corrective Action (FRACA) system was used to track HYSAS reliability. Basically, FRACA is a design/reliability tool used to control product reliability and system safety characteristics within predetermined limits. Control is maintained through Honeywell Malfunction Reports (HMR's) by:

- Recording the initial information concerning a detected or suspected malfunction
- Defining the results of any subsequent analysis
- Classifying malfunctions
- Defining the corrective actions to be taken to eliminate or greatly reduce the effects of any experienced failure

Fifty-six HMR's were issued during this flight testing program. They are provided in Section III of the Data Package. Table 3 summarizes the applicable reliability data listed on each HMR.

Eight of the malfunctions were classified as failures and are therefore relevant to the HYSAS mean time between failure (MTBF) calculations.

Five different reliability characteristics were employed in classifying these HMR's to describe the events surrounding the various deviations

TABLE 3. OPERATIONAL SUITABILITY MALFUNCTION REPORT STATUS

HMR No. - Date	Aircraft/Component	Operating Hours per Unit	Failure Mode	Cause	Classification Operational Suitability/ Future Hardware	Remarks	HMR Status - Date
B02001-4/24/75	TH-57/ Y-6	0	Null Offset	Mishandling	Discrepancy/ Discrepancy	None	Closed 10/16/75
B02002-4/30/75	TH-57 / Y-7	0	Oil Leakage	Design Oversight	Nonrelevant Failure/ 100% Corrected	Drawing change eliminated this failure mode.	Closed 10/16/75
B02003-5/6/75	TH-57/ Y-7	0	Physical Damage	Mishandling	Discrepancy/ Discrepancy	None	Closed 10/16/75
B02004-5/7/75	TH-57/ Y-2	0	Null Offset	Not Verified	Discrepancy/ Discrepancy	None	Closed 10/16/75
B02005-5/5/75	TH-57/ Y-3	0	Oil Leakage	Design Oversight	Nonrelevant Failure/ 100% Corrected	See remarks for HMR B02002	Closed 10/16/75
B02006-5/7/75	TH-57/ Y-3	0	Physical Damage	Mishandling	Discrepancy/ Discrepancy	None	Closed 10/16/75
B02007-5/14/75	TH-57/ Y-4	0	Oil Leakage	Mishandling	Discrepancy/ Discrepancy	None	Closed 7/28/75
B02008-5/19/75	TH-57/ Y-6	6.3	Oil Leakage	Contamination	Failure/ 90% Correctable	Occurrence of this failure mode should be reduced by 90% if clean room is used	Closed 10/23/75
B02009-6/4/75	OH-58/ Y-21	0	Oil Seepage	Design Oversight	Discrepancy/ Discrepancy	Drawing change will eliminate this oil seepage in future builds	Closed 7/12/76
B02010-6/17/75	TH-57/ Y-5	29.5	Servo Binding	Vendor/ Design Oversight	Failure/ 90% Correctable	Vendor design corrections should reduce this failure mode by at least 90%	Closed 10/23/75
B02011-6/17/75	TH-57/ Y-7	30.1	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02010	Closed 10/23/75
B02012-6/20/75	OH-58/ Y-21	3.0	Oil Leakage	Design Oversight	Failure/ 100% Correctable	Drawing change will eliminate this failure in future builds	Closed 7/12/76
B02013-6/23/75	OH-58/ Y-18	0	Physical Damage	Mishandling	Discrepancy/ Discrepancy	None	Closed 10/22/75
B02014-7/9/75	OH-58/ Y-16	8.8	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02010	Closed 10/22/75
B02015-7/11/75	OH-58/ Y-18	0	Null Offset	Not Calibrated	Discrepancy/ Discrepancy	None	Closed 10/22/75
B02016-7/11/75	OH-58/ Y-14	0	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02010	Closed 7/12/76
B02017-7/21/75	TH-57/ Y-5	58.5	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02010	Closed 7/12/76
B02018-7/22/75	TH-57/ Y-4	0	Oil Leakage	Design Oversight	Nonrelevant Failure/ 100% Correctable	See remarks for HMR B02002	Closed 7/12/76
B02019-7/22/75	TH-57/ Y-3	0.5	Oil Leakage	Installation Error	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02020-7/28/75	OH-58/ Y-15, R-2	37.2	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02010	Closed 7/12/76
B02021-7/25/75	OH-58/ Relay	10	System Won't Engage	Low Aircraft Voltage	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02022-8/13/75	TH-57/ Y-3	120	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02012	Closed 7/12/76
B02023-7/21/75	OH-58/ Y-17	22.1	Oil Leakage	Design Oversight	Pattern Failure 100% Correctable	See remarks for HMR B02012	Closed 7/12/76
B02024-8/22/75	TH-57/ Y-8	185.8	Null Offset	Contamination	Failure/ 90% Correctable	Improved cleaning should reduce this failure mode by 90%	Closed 7/12/76

TABLE 3. OPERATIONAL SUITABILITY MALFUNCTION REPORT STATUS (CONTINUED)

HMR No. - Date	Aircraft/Component	Operating Hours per Unit	Failure Mode	Cause	Classification Operational Suitability/ Future Hardware	Remarks	HMR Status - Date
B02025- 9/5/75	OH-58/ Y-18	60.9	Null Offset	Mishandling	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02026- 9/5/75	OH-58/ Y-14, R-2	39	System Will Not Turn On	Mishandling	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02027- 9/8/75	TH-57/ Y-3	176.9	Oil Leakage	Not Verified	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02028- 9/9/75	OH-58/ Y-23	11	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02009	Closed 7/12/76
B02029- 9/16/75	OH-58/ Y-28	68.4	Oil Leakage	Design Oversight	Transferred/ 90% Correctable	Failure transferred to HMR B02035	Closed 7/12/76
B02030- 9/16/75	OH-58/ Y-14, R-5	22	Null Offset	Installation Error	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02031- 10/3/75	TH-57/ Y-5	87.8	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02012	Closed 7/12/76
B02032- 10/8/75	OH-58/ R-10	156.1	Oil Leakage	Salvage Defect	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02033- 10/8/75	OH-58/ Y-22	263.8	Servo Binding	Actuator Linkage Binding	Failure/ 90% Correctable	Linkage design change required for future builds.	Closed 7/12/76
B02034- 10/14/75	OH-58/ Y-28, Y-18	78.5/138.9	System Too Stiff	Installation Error	Discrepancy/ Discrepancy	None 7/12/76	Closed 7/12/76
B02035- 10/16/75	OH-58/ Y-28	78.5	Oil Leakage	Design Oversight	Failure/ 95% Correctable	Transferred from HMR B02029	Closed 7/12/76
B02036- 10/23/75	TH-57/ Y-4	162.5	System Will Not Work	Not Verified	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02037- 10/18/75	OH-58/ R-6	143	Null Offset	Not Verified	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02038- 2/2/76	TH-57/ S/N 2819	412.1	System Noisy	Not Verified	Discrepancy/ Discrepancy	None	Closed 7/12/76
B02039- 3/11/76	OH-58/ R-13	644.3	Servo Binding	Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02033	Closed 5/10/77
B02040- 4/29/76	OH-58/ Y-14	134.3	Servo Will Not Engage	Contamination	Pattern Failure/ 90% Correctable	See remarks for HMR B02024	Closed 5/10/77
B02041- 5/26/76	OH-58/ Y-18	735.3	High Frequency Instability	Not Verified	Discrepancy/ Discrepancy	Unable to verify in laboratory	Closed 5/10/77
B02042- 6/2/76	OH-58/ Y-28	116.3	Oil Leakage	Not Verified	Discrepancy/ Discrepancy	Servo lab tests were unable to detect leakage. However, leakage was traced to an adjacent aircraft fitting.	Closed 5/10/77

TABLE 3. OPERATIONAL SUITABILITY MALFUNCTION REPORT STATUS (CONCLUDED)

HMR No. - Date	Aircraft/Component	Operating Hours per Unit	Failure Mode	Cause	Classification Operational Suitability/ Future Hardware	Remarks	HMR Status - Date
B02043-6/2/76	OH-58/ R-13	816.3	Low Frequency Low Amplitude Oscillation	Not Verified	Discrepancy/ Discrepancy	Ground check of system was unable to duplicate or verify failure condition	Closed 5/10/77
B02044-7/6/76	OH-58/ Y-24	155	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02012	Closed 5/10/77
B02045-7/7/76	TH-57/ Y-6	590	PID Shaft Slippage	Design Oversight	Failure/ 90% Correctable	Drawing change will eliminate this failure mode in future builds	Closed 5/10/77
B02046-7/9/76	OH-58/ Y-20	290	Physical Damage	Mishandling	Discrepancy/ Discrepancy	None	Closed 5/10/77
B02047-7/18/76	OH-58/ Y-24	328	Servo Binding	Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02033	Closed 5/10/77
B02048-7/10/76	TH-57/ Y-3	276	Oil Leakage	Contamination	Pattern Failure/ 90% Correctable	See remarks for HMR B02008	Closed 5/10/77
B02049-8/8/76	TH-57/ Y-8	485	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02012	Closed 5/10/77
B02050-11/9/76	TH-57/ Y-10	781	Poor System Performance	Not Verified	Discrepancy/ Discrepancy	Unable to verify in laboratory	Closed 5/10/77
B02051-12/8/76	OH-58/ Y-19	6	Oil Leakage	Not Verified	Unknown/ Unknown	Controller still in transit from field at conclusion of this program.	Closed 5/10/77
B02052-12/6/76	TH-57/ Y-9	907	Oil Leakage	Not Verified	Discrepancy/ Discrepancy	Unable to verify in laboratory	Closed 5/10/77
B02053-1/17/77	TH-57/ Y-5	634	Null Offset	Null Adjustment Slippage	Failure/ 90% Correctable	Drawing change will reduce the occurrence of this failure mode by 90%	Closed 5/10/77
B02054-1/21/77	OH-58/ Y-28	251	Oil Leakage	Design Oversight	Pattern Failure/ 100% Correctable	See remarks for HMR B02012	Closed 5/10/77
B02055-4/12/76	OH-58/ Y-29	75	Servo Binding	Vendor Design Oversight	Pattern Failure/ 90% Correctable	See remarks for HMR B02033	Closed 5/10/77
B02056-12/15/76	OH-58/ Y-16	376	Oil Leakage	Mishandling	Discrepancy/ Discrepancy	None	Closed 5/10/77

in HYSAS performance. These characteristics, termed malfunction, discrepancy, failure, pattern failure, and nonrelevant failure, are defined below.

Malfunction

A malfunction is defined as any unanalyzed deviation in output performance of the equipment under test from the specification requirements. Once the malfunction is analyzed through the failure reporting and corrective action (FRACA) process, the malfunction is classified as a discrepancy or as a failure.

Discrepancy

A discrepancy is defined as an analyzed malfunction that has one of the following causes.

- Typographical errors in the product documentation that can be corrected by a "records only" type of change. For example, if a certain pressure measurement differs from that of the specification but is eventually proven to be correct, the specification would be corrected and the malfunction classified as a discrepancy.
- Test operator error or defective test equipment. For example, if the operator permitted test cart hydraulic pressures to exceed the safe working pressures of HYSAS, any resulting damage would be classified as a discrepancy.
- Secondary failure. For example, if the aircraft filtration system permitted HYSAS to become contaminated to where

performance deviations were detected, the malfunction would be classified as a discrepancy.

- Incompatibility between elements of product documentation. For example, malfunctions resulting from differences that may exist between HYSAS specifications and those of the aircraft's true requirements would be classified as discrepancies.

Failure

A failure is defined as an analyzed deviation in output performance of the equipment under test from the specification requirements. All failures are relevant to the reliability calculations except those defined below as pattern failures or nonrelevant failures.

Pattern Failure

A pattern failure is defined as the occurrence of two or more failures of the same mode, piece part, or application. If this condition occurs and if an effective corrective action is defined, only the first of such failures is considered in the MTBF calculations. This approach for determining the HYSAS MTBF is reasonable because the equipment tested was considered to be developmental and not mature production hardware.

Nonrelevant Failure

A nonrelevant failure is defined as a failure which occurs prior to any recorded flight time; it is considered nonrelevant to the HYSAS MTBF calculations.

Eight of the experienced malfunctions were classified as HYSAS failures. Table 4 is a list of these failures.

TABLE 4. HYSAS FAILURES

Number of Flight Hours/HYSAS	HMR No.	Failure Description
3.0	B02012	PID "O" ring leak
6.3	B02008	Amplifier "O" ring leak
29.5	B02010	Servoactuator binding before corrective action
78.5	B02035	Electroform buildup causing leakage
175.8	B02024	Amplifier offset due to wax contamination
263.8	B02033	Servoactuator linkage binding - after correction action
376.0	B02053	Controller null adjust slipped
590.0	B02045	PID arm clevis slipped calibration

When the failures listed in Table 4 are plotted against their individually accumulated number of flight hours, Figure 37, an impressive MTBF growth curve is developed. Specifically, after the first 100 flight hours, the growth curve illustrates a definite flattening, suggesting that fluidics should be subjected to a 100-hour manufacture-run-in (MRI) before delivery.

Assuming that each future HYSAS receives a 100-hour MRI, the measured MTBF between this point on the growth curve and the 399-flight-hour point can be calculated by:

$$\text{MTBF (measured)} = \frac{[(399-100)\ \text{hr/HYSAS}]\ (40\ \text{HYSAS's})}{(7-4.25)\ \text{Failures}}$$

$$= 4349\ \text{hrs MTBF}$$

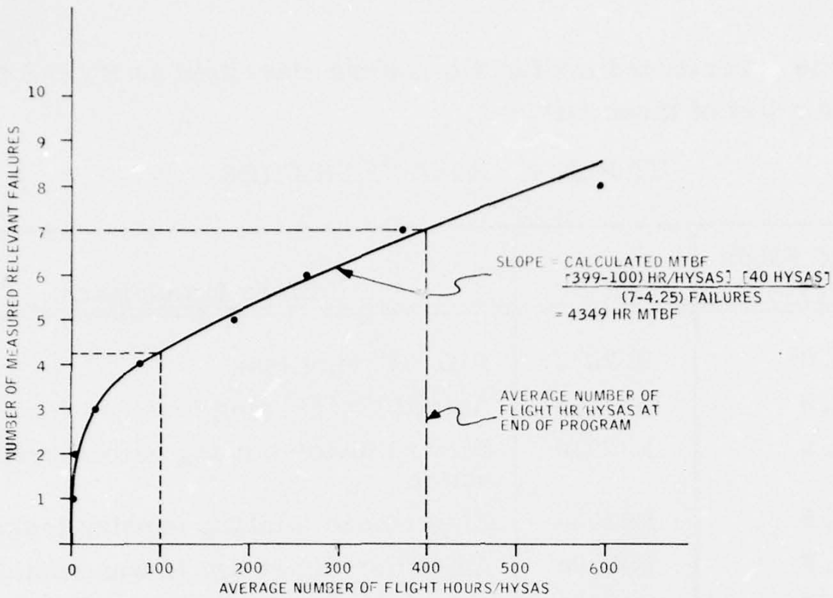


Figure 37. Field Measured MTBF Growth Curve.

It should be noted that the 399-flight-hour point on the growth curve is the average number of flight hours that were accumulated on each HYSAS.

If each HYSAS is subject to a 100-hour MRI and if the corrective actions as defined on each HMR in question are 90-percent effective, it is estimated that similar future HYSAS equipment should exhibit MTBF's on the order of 43,000 flight hours.

Because each HYSAS is made up of a servoactuator assembly and a fluidic controller assembly, it was found during this program how each of these assemblies performed on an individual basis. Also, because the controller experienced fluidic and mechanical component failures, it was found how these types of failures were distributed. Table 4 shows that after a 100-hour MRI or during the time we would expect the 43,000-hour MTBF, four failures were experienced. The MTBF is apportioned to these four hardware failures as follows:

Controller MTBF/Axis = 4/3 x 43,000 = 57,333 hr

Fluidic Component MTBF/Axis = 4 x 43,000 / 172,000 hr

Mechanical Component MTBF/Axis = 2 x 43,000 = 86,000 hr

Servoactuator MTBF/Axis = 4 x 43,000 = 172,000 hr

The number of failures experienced during this flight test program were too few to establish accurate MTBF's at the individual component level. However, based on the average number of individual fluidic and mechanical components used per axis, the total MTBF's of these components were apportioned to the individual component level as follows:

$$\text{Individual Fluidic Component MTBF} = \frac{(\overset{①}{6}\overset{②}{x26}+\overset{③}{5x14}+\overset{④}{4x40})}{40}\ (172{,}000\ \text{hr})$$

$$= 1{,}660{,}000\ \text{hr MTBF}$$

$$\text{Individual Mechanical Component MTBF} = \frac{(\overset{⑤}{6}\overset{⑥}{x26}+\overset{⑦}{3x14}+\overset{⑧}{1x40}+\overset{⑨}{5x26}+\overset{⑩}{4x26})}{40}\ (86{,}000\ \text{hr})$$

$$= 1{,}014{,}800\ \text{hr MTBF}$$

The component MTBFs are based on the following (circled numbers below correspond to the numbers circled above the equations):

(1) The amplifiers, bellows, and rate sensors are considered fluidic components.

(2) The operational suitability program used 26 yaw axis controllers, and each yaw axis controller, in turn, employed five amplifiers and one rate sensor.

(3) The operational suitability program used 14 roll axis controllers, and each roll axis controller, in turn, employed four amplifiers and one rate sensor.

(4) Each of the 40 controllers employed four bellows.

(5) The null/gain adjustments, BIT, PID, and flow control valves are considered mechanical components.

(6) Each yaw axis controller employed six mechanical adjustments.

(7) Each roll axis controller employed three mechanical adjustments.

(8) Each roll axis and yaw axis controller employs one BIT circuit, and each BIT circuit is considered to be equivalent, on a mechanical basis, to a single mechanical adjustment.

(9) Each yaw axis controller employs one PID, and each PID, in turn, is considered to be equivalent, on a mechanical complexity basis, to five mechanical adjustments.

(10) Each yaw axis controller employs one flow control valve, and each flow control valve, in turn, is considered to be equivalent, on a mechanical complexity basis, to four mechanical adjustments.

It should be noted that each of these predicted MTBF's assumes that all corrective actions defined on each HMR will be incorporated into future equipment. It should also be noted that none of these random failure rate calculations include any wearout effects. Even though several HYSAS's have accumulated more than 900 hours, no equipment wearout effects have been detected.

HYSAS MAINTAINABILITY

During the HYSAS operational suitability program, effort was made to define maintainability characteristics of the HYSAS equipment. Results indicate that:

Mean time to replace a malfunctioning component on the flight line is

MTTR (Flight Line) = 1.8 hr

Mean time to isolate a component fault and repair the HYSAS at the depot is

$$\text{MTTR (Depot)} = 0.81 \text{ hr}$$

90 percent of all depot repairs can be accomplished in less than

$$M_{max_{ct}} \ \text{90th Percentile (Depot)} = 1.27 \text{ hr}$$

The way in which these HYSAS maintainability characteristics were determined is described in this subsection.

HYSAS Maintenance Concept

The HYSAS consists of a single line replaceable unit (LRU) for each axis of control. At the flight line, all preflight testing was accomplished by means of built-in test (BIT). If BIT determined that any of the HYSAS equipment was not functioning properly, a ground testing cart was used to isolate the fault. If the failure was verified to HYSAS, the LRU was replaced with an LRU that was known to function within specification requirements.

Whenever a HYSAS LRU was removed from the aircraft, it was sent to the depot for repair. In this case, Honeywell served as the depot. At Honeywell all incoming HYSAS equipment was installed on a hydraulic test bench for failure verification and isolation. Once the failure was verified and isolated, the faulty LRU was repaired by replacement of the faulty piece part or assembly.

Maintainability Measurements Taken

The HYSAS repair times demonstrated at the flight line are given in Table 5.

TABLE 5. HYSAS CORRECTIVE MAINTENANCE TIME FOR FLIGHT LINE

Maintenance Task Elements	Average Time (Minutes)
1. Isolate Problem (Not Usually Required)	6
2. Remove Transmission Cowling and Quick Disconnect	7
3. Remove Drain Tube in Luggage Compartment	5
4. Remove Magnetic Brake and Force Gradient	5
5. Disconnect Pedal Pushrod	2
6. Disconnect Aft Pushrod	2
7. Disconnect Three Hydraulic Hoses	2
8. Disconnect Electrical Connector	1
9. Remove Three Mounting Bolts	5
10. Remove HYSAS and Mount from Aircraft	5
11. Remove and Replace HYSAS on Mount	20
12. Replace HYSAS in Aircraft (Elements 2 through 10)	34
13. Check Rigging and Verify Repair	20
Total	114
MTTR (Flight Line) = 114 minutes or 1.9 hours	

HYSAS depot repairs demonstrated at Honeywell during the Operational Suitability Program consisted of repairing LRU's with faulty:

- Pilot Input Devices (PID)
- Flow Control Valves

- Built-in Test (BIT) Equipment
- Bellows
- Rate Sensors
- Amplifiers
- Mechanical Null/Gain Adjustments
- Servoactuators

Figure 38 is a block diagram of the maintenance tasks performed to demonstrate these repairs. As indicated, the HYSAS is completely repairable at the depot except for the servoactuators. Servoactuators were returned to Hydraulic Research Textron (manufacturer) for repair and servicing. During a full operational program, all HYSAS repairs could be accomplished at the intermediate level.

Maintenance Math Models

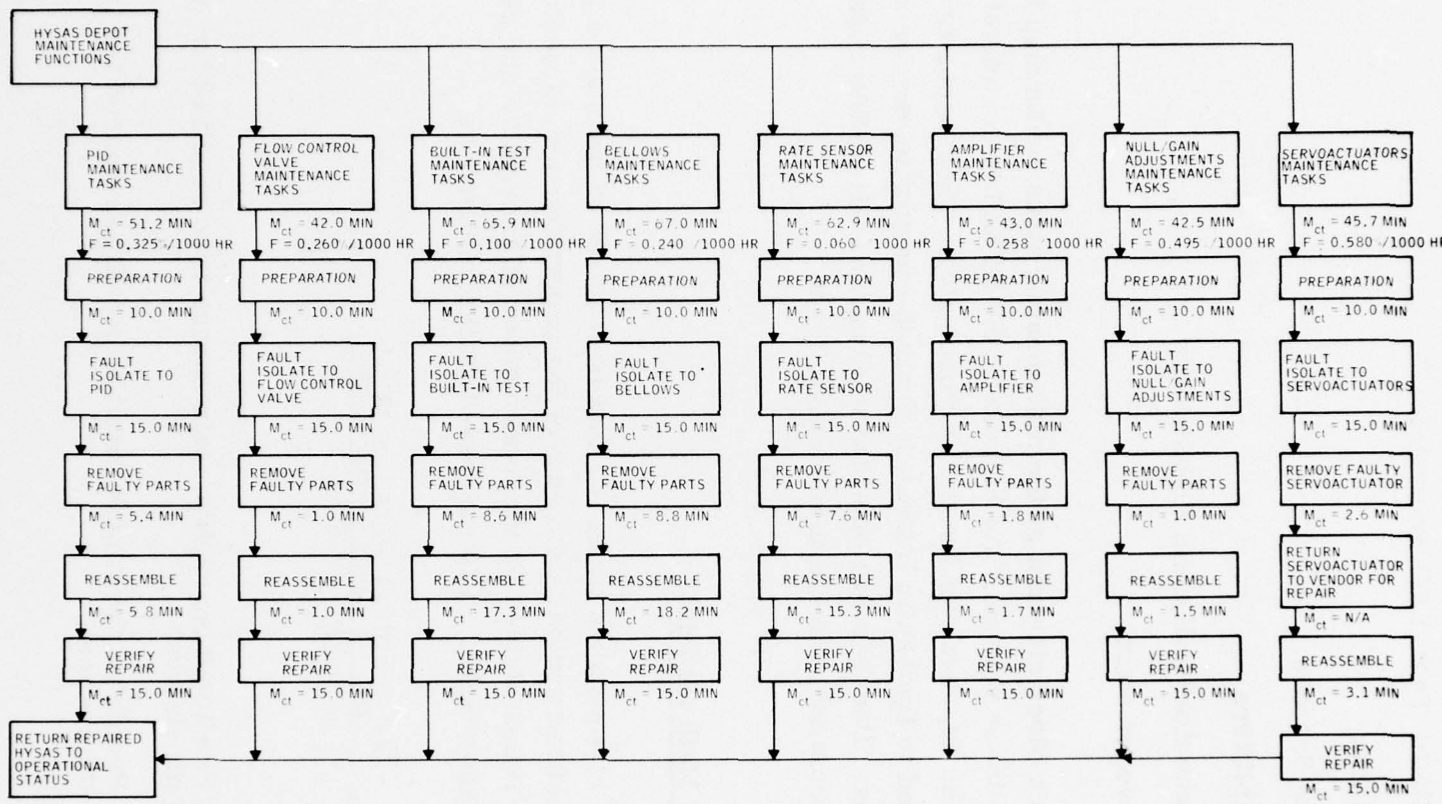
The average maintenance time, $\overline{M}$, that is required to maintain a product for a specified period is the sum of the preventive and corrective maintenance times divided by the total number of preventive and corrective maintenance tasks. It is expressed mathematically as

$$\overline{M} = \frac{\Sigma(F_{ci} \times M_{cti}) + \Sigma(F_{pi} \times M_{pti})}{\Sigma(F_{ci} + F_{pi})}$$

where

M_{cti} = Predicted corrective maintenance time required for the ith element

M_{pti} = Predicted preventive maintenance time required for the ith element.



* THE MAINTENANCE FREQUENCIES ARE BASED ON THE TOTAL FAILURE RATE OF THE AVERAGE NUMBER OF COMPONENTS IN SYSTEM.

Figure 38. HYSAS Repair Time Estimates for Depot Repair.

F_{ci} = Corrective maintenance task frequency for the ith element (percent failures per 1000 flight hours).

F_{pi} = Preventive maintenance task frequency for the ith element (percent actions required per 1000 flight hours).

Because no preventive maintenance actions are anticipated for HYSAS, this relationship is reduced to

$$\text{Mean Time to Repair (MTTR)} = \frac{\Sigma(F_{ci} \times M_{cti})}{\Sigma F_{ci}} \qquad (4)$$

The 90 percentile of the maximum corrective maintenance time ($M_{max_{ct}}$) is determined by:

$$\text{90th Percentile } (M_{max_{ct}}) = \text{Antilog (Base}_e) \left[\frac{\sum_{i=1}^{n_c} F_{ci}(\ln M_{cti})}{n_c} + \psi \sqrt{\frac{\sum_{i=1}^{n_c} F_{ci}(\ln M_{cti})^2 - \frac{\left(\sum_{i=1}^{n_c} F_{ci}(\ln M_{cti})\right)^2}{n_c}}{n_c - 1}} \right] \qquad (5)$$

where

ψ = 2.33 (the value of the independent variable log-normal function which corresponds to the 90th percentile point $M_{max_{ct}}$).

n_c = Total number of corrective maintenance tasks = ΣF_{ci}

Prediction Calculations

The various elements exhibited in Equations 4 and 5 were determined by the techniques given in Table 6. Using these elements in conjunction with Equation (1), the HYSAS MTTR for depot maintenance has been calculated:

$$MTTR_{(Depot)} = \frac{113.014}{2.318} = 48.75 \text{ min or } 0.81 \text{ hr}$$

Likewise, the HYSAS $M_{max_{ct}}$ for intermediate maintenance has been determined:

$$\text{90th Percentile (Depot)} \; (M_{max_{ct}}) = ln^{-1} \frac{8.981}{2.318} + 2.33\sqrt{\frac{34.848 - \frac{(8.981)^2}{2.318}}{2.318 - 1}}$$

$$= 76.28 \text{ min or } 1.27 \text{ hr}$$

MEASURED RELIABILITY OF AN EXISTING ELECTROMECHANICAL HELICOPTER SCAS

The reliability of the operational suitability equipment and similar existing electromechanical systems were compared. The Huey Cobra Gunship was the only vehicle equipped with a SCAS that compares on a functional basis (vehicle rate detecting/damping, pilot input control, and built-in test) to Honeywell's operational suitability equipment. The service records for these helicopters are located at AVSCOM (St. Louis).

Three different recordkeeping systems were employed by AVSCOM. The first two reporting systems, entitled Management Summary Reports and Flat Rate Manuals, were employed by the Army from 1970 through 1975.

TABLE 6. ELEMENTS NEEDED TO CALCULATE MTTR AND $M_{max_{ct}}$ (DEPOT)

	Corrective Maintenance Time M_{cti} (min)	Frequency F_{ci} (%/1000 hr)	$(M_{cti})(F_{ci})$	$F_{ci}(\ln M_{cti})$	$F_{ci}(\ln M_{cti})^2$
PID	51	0.325	16.575	1.279	5.024
Flow Control Valve	42	0.260	10.920	0.972	3.632
Built-in Test	66	0.100	6.600	0.419	1.755
Bellows	67	0.240	16.080	1.009	4.243
Rate Sensor	63	0.060	3.780	0.249	1.039
Amplifier	43	0.258	11.094	0.970	3.650
Null/Gain Adjustments	43	0.495	21.285	1.862	7.003
Servoactuators	46	0.580	26.680	2.221	8.502
Totals		2.318	113.014	8.981	34.848

Although these reporting systems contained reliability deficiencies, the records indicate that the Huey Cobra SCAS should have reached a mature state of reliability. Basically, these records show that 620 of the gunships have been accumulating on the order of 200,000 flight hours per year since 1970. This amounts to more than one million hours to date.

In early 1976, AVSCOM set up an entirely new, rigorous maintenance data collection system called Reliability, Availability, Maintainability/ Logistics (RAM/LOG). This data collection system evaluates contractor performance in the areas described by the system's title. RAM/LOG has been used in several test cases. One of these was a flight testing program of an updated Huey Cobra Gunship, the YAH-1S, during the summer of 1976 at Fort Rucker. Although this aircraft contained several new features, the SCAS remained unchanged from previous aircraft. RAM/LOG indicated that the YAH-1S SCAS experienced

22 maintenance actions, 13 chargeable failures, and 7 mission aborts during 600 flight hours. Reasons ranged from electronic circuit failures to gyro sensor failures. Based on this data, estimates of the Huey Cobra's SCAS mean time between unit removals (MTBUR) and mean time between failures (MTBF) are calculated:

$$\text{MTBUR} = \frac{\text{Total Flight Hours}}{\text{Total Maintenance Actions}}$$

$$= \frac{600 \text{ x } 3 \text{ axis}}{22}$$

82 Flight Hours

$$\text{MTBF} = \frac{\text{Total Flight Hours}}{\text{Total Failures}}$$

$$= \frac{600 \text{ x } 3 \text{ axis}}{13}$$

139 Flight Hours

These estimates were made on a per axis basis to be compatible with the reliability methods being used on the HYSAS Operational Suitability Program.

PREDICTED RELIABILITY OF AN ELECTROMECHANICAL HELICOPTER SCAS

A reliability prediction for an electromechanical three axis SCAS that is intended for use in modern helicopters is provided in Table 7. On a per axis basis, this equipment would exhibit a failure rate of (89.348%/1000 hr ÷ 3) = 29.783% and a resulting MTBF of 3,360 hours. This MTBF is contingent on the use of military level parts, a full qualification program, and an MRI on all assembled equipment before it is delivered to the customer.

TABLE 7. ELECTROMECHANICAL THREE-AXIS SCAS RELIABILITY PREDICTION

Part Type	Failure Rate, λ (%/1000 hr)	Quantity Per SAS (N)	N λ (%/1000 hr)
Capacitor, ceramic	0.003	63	0.189
Capacitor, wet slug	0.043	21	0.903
Capacitor, solid tantulum	0.020	25	0.500
Choke	0.013	3	0.039
Connector	0.070	15	1.050
Diode	0.009	94	0.846
Integrated Circuit	0.100	96	9.600
Printed Circuit Board	0.010	9	0.090
Relay	0.116	9	1.044
Resistor, Carbon Comp.	0.001	114	0.114
Resistor, Film	0.005	301	1.505
Resistor, Wire Wound	0.010	8	0.080
Transformer, Power	0.145	1	0.145
Transistor, Signal	0.013	49	0.637
Transistor, Power	0.071	6	0.426
Transistor, FET	0.015	12	0.180
LVDT	1.000	3	3.000
Rate Gyro (includes gyro wearout)	20.000	3	60.000
Servoactuator and Valve	3.000	3	9.000
		Total Failure Rate =	89.348

RELIABILITY COMPARISONS BETWEEN THE HYSAS AND ELECTROMECHANICAL HELICOPTER SCAS

The demonstrated MTBF for the HYSAS was 4,349 hours; the projected MTBF is 43,000 hours. Two completely different methods were used to compare the reliability of the HYSAS with an equivalent electromechanical SCAS.

Measured reliability of the Huey Cobra SCAS was calculated to be 139 flight hours per axis using AVSCOM's new RAM/LOG maintenance data collection system. This reliability figure is much too low to be considered representative of a typical electromechanical SCAS in a program employing comprehensive reliability practices. Factors that may have caused this unrealistic reliability calculation are as follows:

- The YAH-1S SCAS may be sufficiently different from previous SCAS systems to make it "immature hardware" (i.e., reports that the YAH-1S SCAS is unchanged from previous SCAS systems may be in error).
- The Huey Cobra SCAS (all models) may not be controlled under a comprehensive reliability program that includes items such as: (1) failure reporting and mandatory corrective action, and (2) a factory burn-in of all production systems.
- RAM/LOG may always yield lower reliability data than the previous reporting systems.

It was beyond the scope of this program to investigate these factors to determine the cause of the unrepresentative data for the Cobra SCAS; however, an additional analysis was performed to calculate the reliability of a typical electromechanical SCAS using the same ground rules that were applied to the HYSAS (i.e., developed in conjunction with a comprehensive reliability program).

Reliability of a single axis of an electromechanical SCAS was calculated using established failure rates for each of its components. This calculated MTBF of 3,360 hours per axis should be compared with the 43,000-hour MTBF of the HYSAS. The difference is attributed to the electromechanical rate gyro, which makes up 67 percent of the electromechanical failure rate. This weak area of the electromechanical system is the most reliable area of the HYSAS, as the hydrofluidic vortex rate sensor is about as reliable as a single-stage fluid amplifier.

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SECTION VI
CONCLUSIONS

- The reliability of the HYSAS is substantially better than that of an equivalent electromechanical SCAS. Demonstrated MTBF for the HYSAS was 4,349 hours, and this MTBF is projected to be 43,000 hours if the required corrective actions are implemented in a future program. Projected reliability for a similar electronic SCAS is 3,360 hours if a comprehensive reliability program is used. Burn-in of all units as well as a failure reporting system with associated corrective actions is required to obtain this projected electronic SCAS reliability.

- The reliability and maintainability advantage demonstrated on this program makes fluidics a clear choice for applications of similar complexity.

- Failure rates for conventional moving part rate gyros are greater than those of a complete fluidic controller. Indications are that the fluidic controller will not wear out over the life of the aircraft.

- Military maintenance personnel are fully capable of maintaining the fluidic systems used in this program.

- An electronic test set is not required for maintenance; no special tools are required.

- HYSAS operate satisfactorily using the existing aircraft hydraulic supplies.

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