FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

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DEVELOPMENT OF A MICROINCH ACTUATOR

Contract NAS 1-7018

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NASA CR-66626

DEVELOPMENT OF A MICROINCH ACTUATOR

By John M. Varga

Prepared under Contract No. NAS 1-7018
FAIRCHILD HILLER CORPORATION
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Farmingdale, New York 11735

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

This report discusses the contractor's efforts to develop a stepping actuator capable of making linear displacements of 0.5×10^{-6} inches. The basic device consists of three sets of piezo-electric crystals, two sets of which operate as clutches and the third as an extender element. Several variations of the basic design are covered, the governing physical laws are reviewed, and the design approach is explained. The device was capable of reliable motions in the desired range with force levels of up to one pound.

SECTION I
INTRODUCTION

The Final Report is presented in satisfaction and completion of Contract NAS 1-7018, issued by the Langley Research Center of the National Aeronautics and Space Administration.

In this contract the Republic Aviation Division of Fairchild Hiller Corporation undertook to develop and manufacture three micro-inch actuators. Each actuator having the capability of,

1) making displacements of one-half a micro-inch per step (5×10^{-7} inches per step),
2) moving at a rate of 3×10^{-4} inches per second, and
3) working against an opposing force of 1000 grams.

Based on past experience in the field of electrostrictive devices Republic approached this problem by utilizing an electrostrictive "inching" unit with successive electrostrictive gripping units.

The nature of the electrostrictive action results in small motions, which is advantageous for the inching unit but also results in small clearances at the gripping unit. Various manufacturing techniques have been developed to circumvent the problem of small gripping motions along with extremely precision surface finishes, all have resulted in the generation of a micro-inch actuator presented in completion of this contract.

SECTION II

OPERATION AND GENERAL CONFIGURATION

The conceptual configuration of the actuator is illustrated in Figure 1. This shows that the device is essentially composed of two portions; a clutching unit and an extender unit. Both units are basically electrostrictive ceramic devices that rely upon the change in size of the ceramic on application of a voltage to produce small motions.

Clutches B and C produce differential gripping action against the walls of the actuator housing. Extender A, performs a longitudinal extending motion against the opposing load, and becomes the "piston" of the more common actuators.

The sequence of events to obtain an extension of the actuator is as follows:

1) With zero voltage applied clutch B and C grip on the outer walls of the actuator housing. (Metal is preferred at these locations as being more able to take the tensile loads generated by the outward force of the clutches.)

2) Voltage is applied to the elements of clutch B, causing a contraction of this unit, which releases the upper portion of the extender unit.

3) Voltage is applied to A, the extender unit, causing this element to expand and shift up the metal end by one step (5×10^{-7} inches).

4) Voltage is removed from clutch B which locks the clutch position.

5) Voltage is applied to clutch C to release the lower portion of extender, A.

6) Voltage is removed from A allowing it to return to its original length, which pulls the lower portion up to the upper section.

7) Voltage is removed from clutch C which grips the extender unit. A one-step extension of 5×10^{-7} inches has now been obtained between the outer actuator housing and the center clutch assembly.

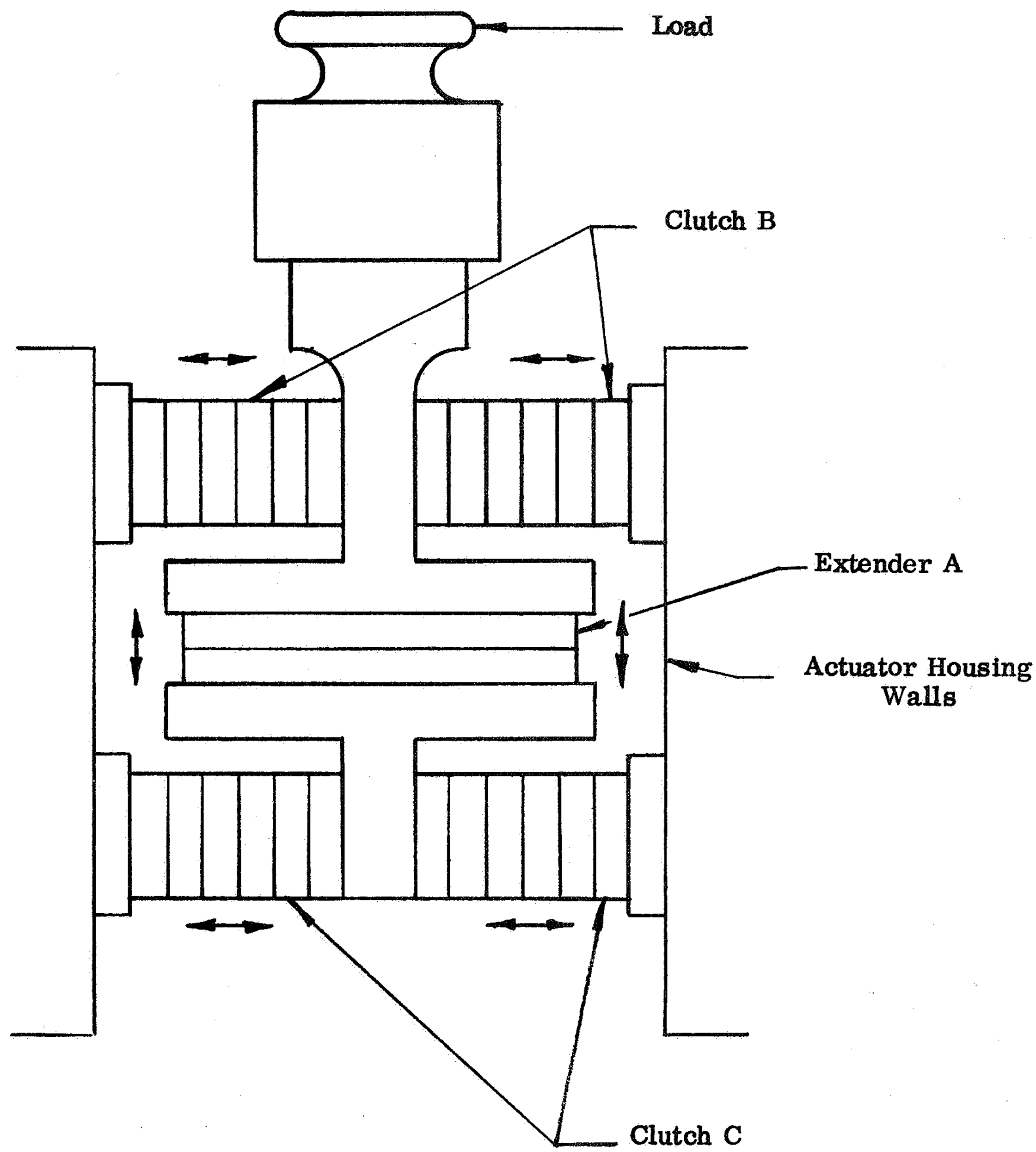

Figure 1. Conceptual Configuration

To obtain a contraction of the unit, the same voltages are applied in the same polarity to the unit but starting with the release of clutch C, thus:

1) No voltage - unit locked in position.
2) Clutch C releases.
3) Unit A extended (now downwards).
4) Clutch C applied.
5) Clutch B released.
6) Unit A to normal length.
7) Clutch B reapplied - no voltage.

Since the voltage applied to the extender unit is relatively small (10.73 volts for 5×10^{-7} inch displacement) an additional "high speed" mode of operation is also available on the actuator.

By simply switching the clutch voltage, or some portion of it, on to the extender a larger step per pulse will be produced and the actuator can cover a larger travel in a given time.

Two individual control consoles have been manufactured. One having a variable rate from 0.0 to 20.0 micro-inches per step, and the second having a stepped rate of 0.50; 1.0; 5.0 micro-inches per step.

SECTION III
ACTUATOR EVOLUTION

A. BACKGROUND

Initially, a cylindrical configuration was considered, the operation of which is identical to that described in Section I. The primary difference was in the configuration of the clutch elements. The cylindrical configuration had 24 "pie" or stave shaped elements arranged in a circular ring as opposed to the stacked elements of the rectangular configuration. The primary reason for the redesign was manufacturing difficulties of the stave shaped ceramic elements.

An initial order was placed with the Clevite Corporation in Bedford, Ohio, to manufacture the required number of piezoelectric ceramic elements using PZT-5H material. These elements were cut, ground and electroded but failed during the polarization process. A second group of staves were prepared and a similar failure occurred. It was suspected that the isostatic pressing of the basic form was at fault, and a third attempt was made starting with a fresh pressing of ceramic powder.

B. FIRST GENERATION ACTUATOR

In an attempt to obviate the necessity of further delays emanating from such material failures, a new actuator configuration had been derived, and is depicted in Figure 2. This shows that the unit is rectangular in shape, it has the same volumetric size as the original actuator but possesses a number of advantages.

First the outside unit - a rectangular tube - is assembled from high quality but readily available components. Standard gage blocks are used to form the two working surfaces that the clutches operate against. These blocks provide surfaces that are flat to a few microinches with surface finish of less than 1 microinch rms quality. Another gage block is used in the center of the unit during assembly to provide dimensional accuracy and parallelism of the working surfaces again to a few microinches. In this manner the specially produced bores of the extender unit, requiring careful honing, are obviated.

Second the clutch unit no longer used specially produced staves but was formed of stacked strips cut from ready, fully prepared, piezoelectric plate. The extender

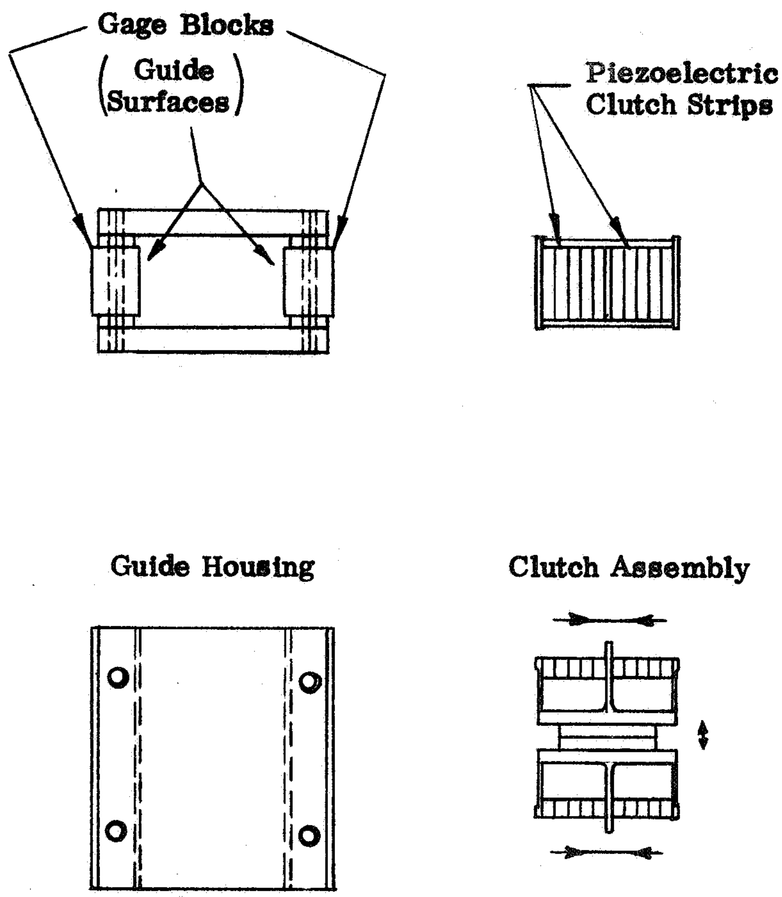

Figure 2. Actuator Components (Full Size)

was also made from similar available piezoelectric strips. Utilizing this approach it was anticipated that the development troubles of special components would be circumvented. Additionally, it was expected that the new clutches would have at least 50% increased motion, an excursion of 93 microinches being indicated for the same 400 volt driving signal and power.

Figures 3 (PC072D0010; 4 (PC072D0011); 5 (PC072D0012) are the manufacturing drawings of the actuator details, with Figure 6 (PC072D0004) depicting the assembly.

Depicted in Figure 7 are the details ready for the assembly of an actuator. The rectangular tube is shown clamped together ready to have assembly holes installed. Due to the hardness of the materials used, these holes were "eloxed" through. The gage block shown on the left was used in the center of the tube to insure the dimensional accuracy required during assembly.

The subassembly shown on top of the aforementioned gage block is one of the two clutch elements required. This clutch element depicts the piezoelectric strips interfaced with 0.002" copper shims and center plate. It is this plate that finally acts as the "piston" of the actuator. The remaining piezoelectric strips and center plate constitute the pieces required for the second clutch. Copper shims are also required but are not shown.

The extender piezoelectric plates are visable between the two "U" elements, and once assembled, using electrical conductive epoxy and foil, constitute the basic "H" section shown. The previously mentioned clutch elements, after assembly, were installed into both open ends of the "H" section and this configuration is the basic clutch mechanism.

Several assembly techniques were studied in order to produce as accurate a housing as possible. The first of the "first generation" actuator housings was assembled in the following manner. Two 0.250" gage blocks were wrung on either side of a 0.750" gage block. This assembly was aligned on a precision surface plate and clamped in position using a pair of parallel clamps. This procedure assure that the two working surfaces (the 0.250 gage blocks) on which the clutches operate will be parallel in both planes to within a few microinches.

PC 072 D 0010

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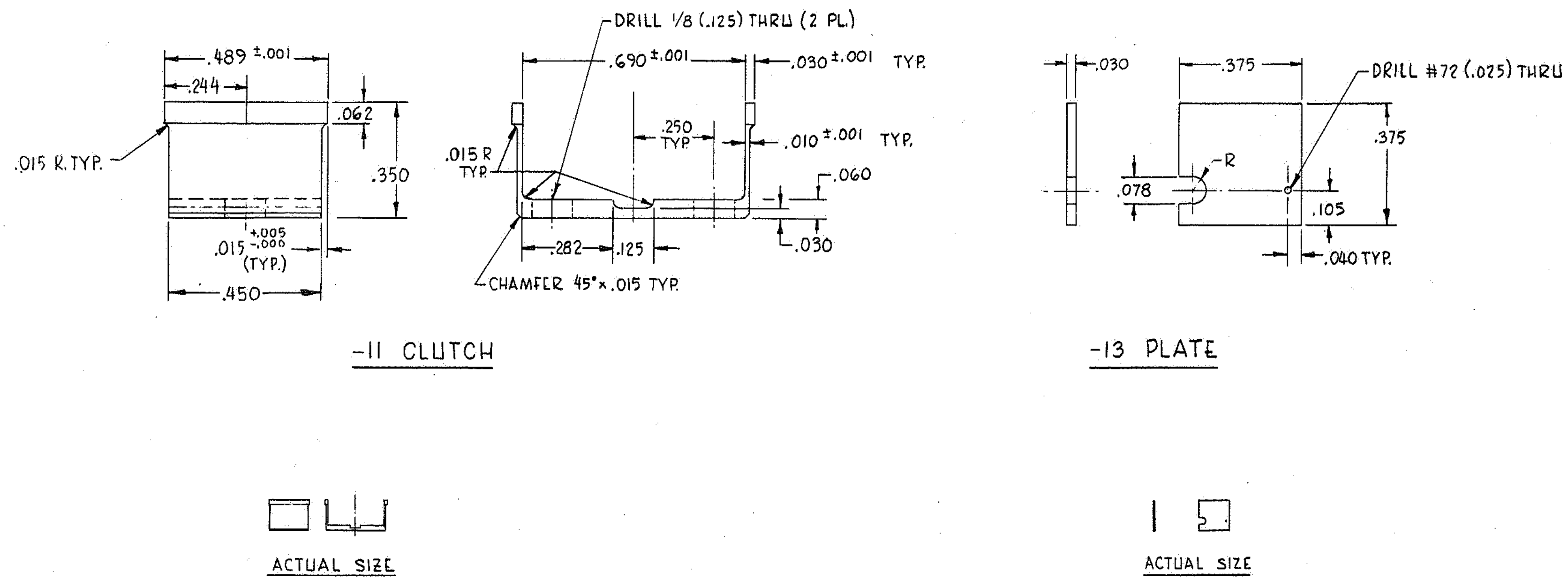

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				-13		PLATE	.030	.4	.4		INVAR			
				PC072D0010-11		CLUTCH		.375	.52	.76	INVAR			

STOCK SIZE

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

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APPLICATION		QUANTITY REQD	

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UNLESS OTHERWISE NOTED

DEC TOL	SH MET. RAD
2 PLACE ±.	BEND:
3 PLACE ±.005	COR:
ANGULAR ±1/4°	DEBURR ALL EDGES

APPLICABLE SPECIFICATIONS

FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE

DO NOT SCALE DRAWING

DRAWN	J. VARGA	4-19-67
CHECKED		
GR ENGR		
STRUCT		
WEIGHTS		
PROJ ENGR		

CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

CLUTCH DETAIL - MICROACTUATOR

SIZE	CODE IDENT NO.	
C	77751	PC 072 D 0010

SCALE 4 X UNLESS OTHERWISE NOTED SHEET 1 OF 1

FORM RAD 141

PC 072 D 0010

FIGURE 3

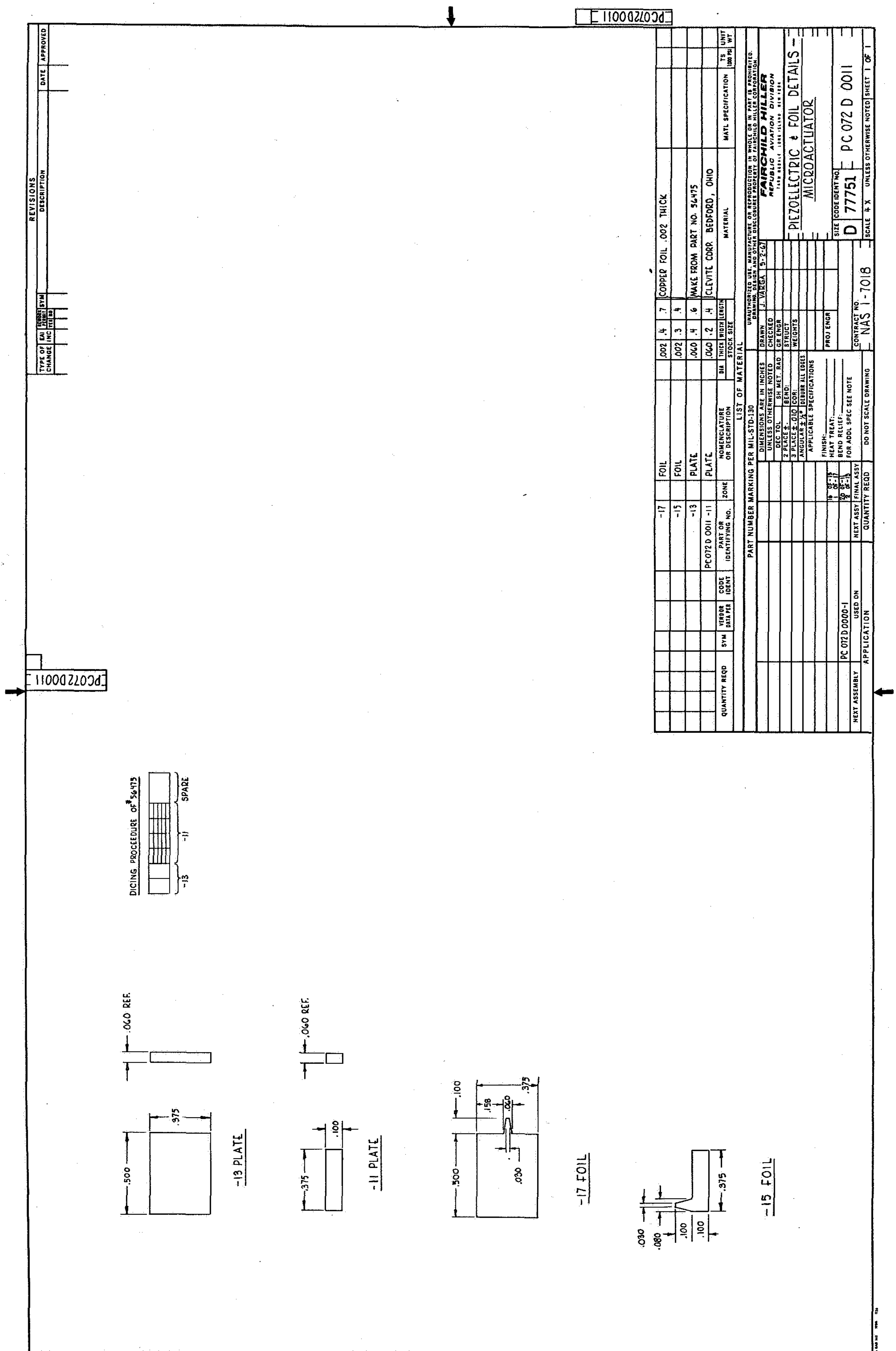
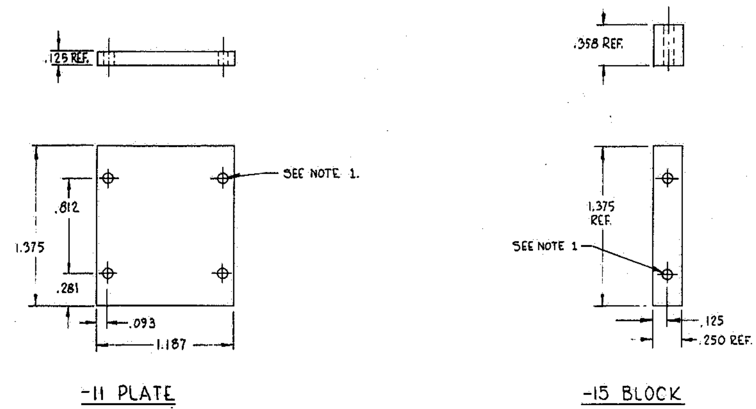
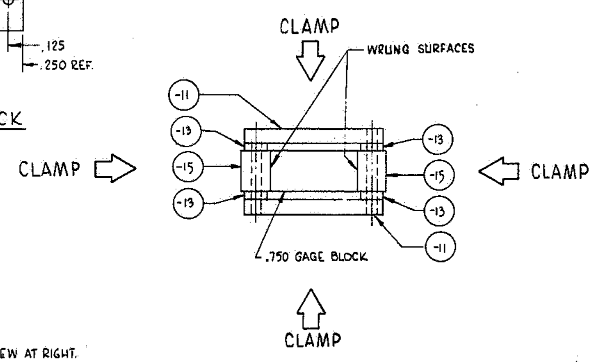
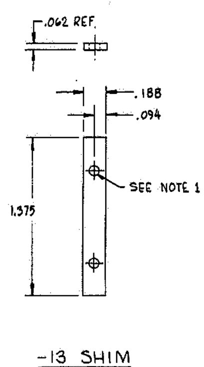

PC072D0011
REVISIONS
PIEZOELECTRIC & FOIL DETAILS — MICROACTUATOR
FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
D 77751 PC 072 D 0011
SCALE 4 X
SHEET 1 OF 1
CONTRACT NO. NAS 1-7018
DRAWN J. VARGA 5-2-67
PC 072 D 0000-1
PART NUMBER MARKING PER MIL-STD-130
LIST OF MATERIAL
-17 FOIL .002 .4 .7 COPPER FOIL .002 THICK
-15 FOIL .002 .3 .4
-13 PLATE .060 .4 .6 MAKE FROM PART NO. 56475
PC072 D 0011 -11 PLATE .060 .2 .4 CLEVITE CORP. BEDFORD, OHIO
DO NOT SCALE DRAWING
DICING PROCEEDURE OF # 56475
-13
-11
SPARE
-13 PLATE
-11 PLATE
-17 FOIL
-15 FOIL
.060 REF.
.500
.375
.100
.158
.060
.030
.080

FIGURE 4







NOTES:

1. DRILLING PROCEEDURE. SEE VIEW AT RIGHT.
   - A. WRING ONE -15 BLOCK ON EACH SIDE OF A .750 GAGE BLOCK AND CLAMP TOGETHER.
   - B. POSITION THE FOUR -13 SHIMS AND TWO -11 PLATES AND CLAMP.
   - C. "ELOX" FOUR HOLES .088±.001 DIA. WITH CLAMPS IN POSITION.

PC072D0012

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS (1000 PSI)	UNIT WT
				-15		BLOCK					MAKE FROM 0.250 GAGE BLOCK	L.S. STARRETT CO.		
				-13		SHIM		.0625			MAKE FROM #496 GROUND FLAT STOCK	ATHOL MASS.		
				PC072D0012 -11		PLATE					MAKE FROM #364B STL. PARALLELS			

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

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	PC 072 D 0000 -1		2 OF -11, -15; 4 OF -13
APPLICATION		QUANTITY REQD	

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED
DEC TOL — 2 PLACE ±; 3 PLACE ±.010; ANGULAR ±1/2° — SH MET. RAD; BEND:; COR:; DEBURR ALL EDGES
APPLICABLE SPECIFICATIONS
FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE
DO NOT SCALE DRAWING

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GR ENGR
STRUCT
WEIGHTS
PROJ ENGR
CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION

HOUSING DETAILS — MICROACTUATOR

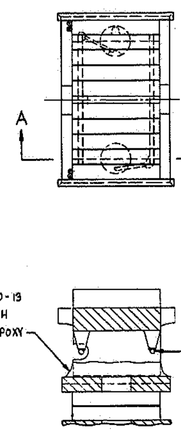
SIZE D | CODE IDENT NO. 77751 | PC 072 D 0012
SCALE 2X | UNLESS OTHERWISE NOTED | SHEET 1 OF 1

REVISIONS: TYPE OF CHANGE | EAI INC | REWORK PERMIT YES NO | SYM | DESCRIPTION | DATE | APPROVED

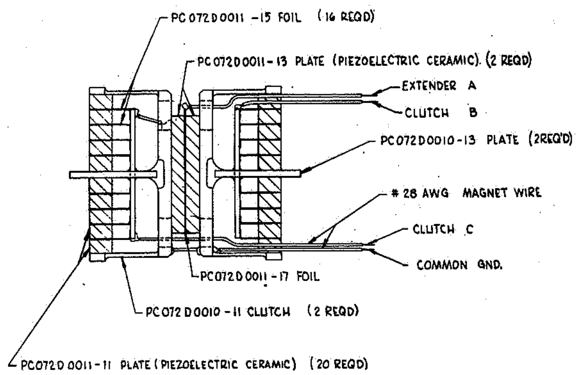
FIGURE 5

TYPE OF CHANGE	EAI INC	SEWORD PERMIT YES / NO	SYM	REVISIONS DESCRIPTION	DATE	APPROVED

PC072D0004



SECTION A-A



-1 CLUTCH ASSEMBLY

NOTES:
1. CONSULT ENGINEERING FOR ASSEMBLY PROCEEDURE.

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	STOCK SIZE (DIA / THICK / WIDTH / LENGTH)	MATERIAL	MATL SPECIFICATION	TS (1000 PSI)	UNIT WT
✓				#24 AWG		COPPER WIRE					
✓				#28 AWG		MAGNET WIRE					
✓				#2015-1		ELECTROBOND EPOXY		ADHESIVE ENGINEERING SAN CALIF.			
✓						TORR-SEAL EPOXY		VARIAN ASSOC. PALO ALTO, CALIF.			
1				PC072D0011 -17		FOIL					
16				-15		FOIL					
20				-13		CLUTCH					
2				PC072D0011 -11		EXTENDER					
1				PC072D0010 -13		PLATE					
2				PC072D0010 -11		CLUTCH					
-1				PC072D0004 -1		CLUTCH ASSY					
						ASSEMBLIES					

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED
DEC TOL | SH MET. RAD
2 PLACE ± | BEND:
3 PLACE ± | COR:
ANGULAR ± | DEBURR ALL EDGES
APPLICABLE SPECIFICATIONS
FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE
DO NOT SCALE DRAWING

NEXT ASSEMBLY | USED ON | NEXT ASSY | FINAL ASSY
APPLICATION | QUANTITY REQD

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FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

CLUTCH ASSEMBLY-
MICROACTUATOR

SIZE D | CODE IDENT NO. 77751 | PC072D0004
SCALE 4X UNLESS OTHERWISE NOTED | SHEET 1 OF 1

PC072D0004

FIGURE 6

On each side of the 0.250 gage blocks were placed the four shims, manufactured from precision ground flat stock, and the two side plates which were manufactured from hardened precision ground steel parallels. This assembly was aligned and clamped together and then set in the "elox" fixture for the insertion of the assembly holes. After removal from the elox fixture a diamond slurry and brass ream rod were used to open the holes to their proper diameter and spring pins pressed into place.

The clamps were released and the 0.750 gage blocks removed. This assembly constitutes a completed actuator housing in which the clutch assembly operates. Subsequently, some difficulty had been experienced "eloxing" the assembly holes in the second and third actuator housing. As a result present housings are assembled using epoxy exclusively.

The assembly of the clutch elements required more elaborate fixtures and step by step process. Room temperature curing of the silver filled epoxy had to be used since any elevated temperature for a faster cure could possibly cause depolarization of the piezoelectric material. The subassembly shown on top of the gage block depicted in Figure 7 was the first portion to be assembled. This clutch element is composed of a center plate, 8 copper shims and ten piezoelectric strips. After application of the epoxy this assembly was placed into a gage block fixture to maintain an overall length of 0.68600 inches in the direction of the clutch excursion.

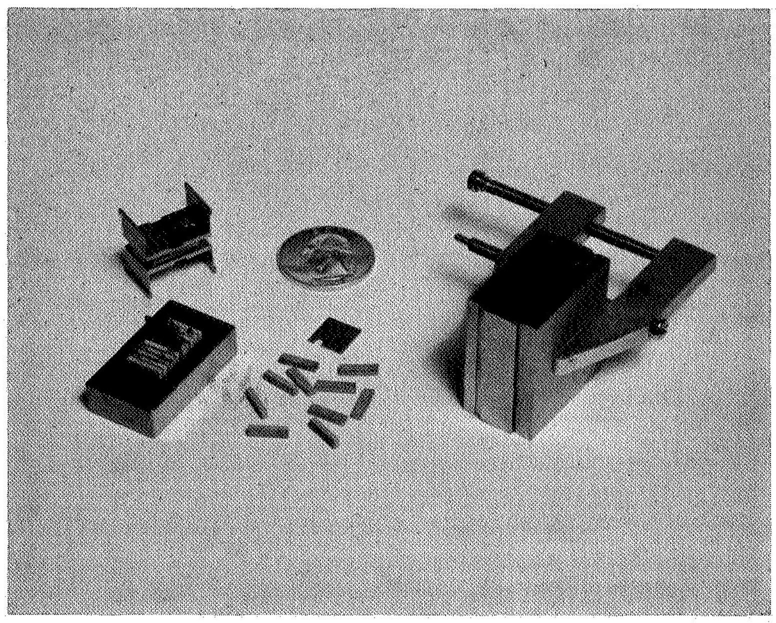


Figure 7. Detail Actuator Elements

After curing, and the removal of the clutch elements from the fixture, the clutch was inserted into a simulated housing composed of clamped gage blocks and driving voltage was applied. It was definitely apparent that when the 600 Hz signal was applied the clutch moved freely within the fixture and when voltage was removed, a considerable effort had to be applied to result in an equal motion.

The two extender elements and the copper foil were also assembled and allowed to cure. The next step was to assemble the two individual "U" elements onto each side of the extender elements, again achieved in a gage block fixture. At this point the clutch appeared as the H section depicted in Figure 7.

The previously mentioned clutch elements were now installed into both open ends of the "H" section. For this another gage block fixture was prepared. In order to insure that epoxy remained between the piezoelectric ceramic and the invar "H" section, the legs of the clutch were opened to about 0.770 (normally 0.750) on each open end. Epoxy was applied, the assembly placed into the fixture, and allowed to cure for 24 hours. Upon removal, Figure 8 was photographed, and at this point it was noticed that the bonding between the ceramic and invar "H" section had broken away. All four joints were therefore separated and this assembly procedure repeated. Twice again failure occurred. Close examination under a 60 X microscope revealed that the bond between the invar and epoxy was the weak link. It was also suspected that the tension of the "H" section which was opened to 0.770 as opposed to the 0.750 dimension of the fixture, could also be a contributing cause.

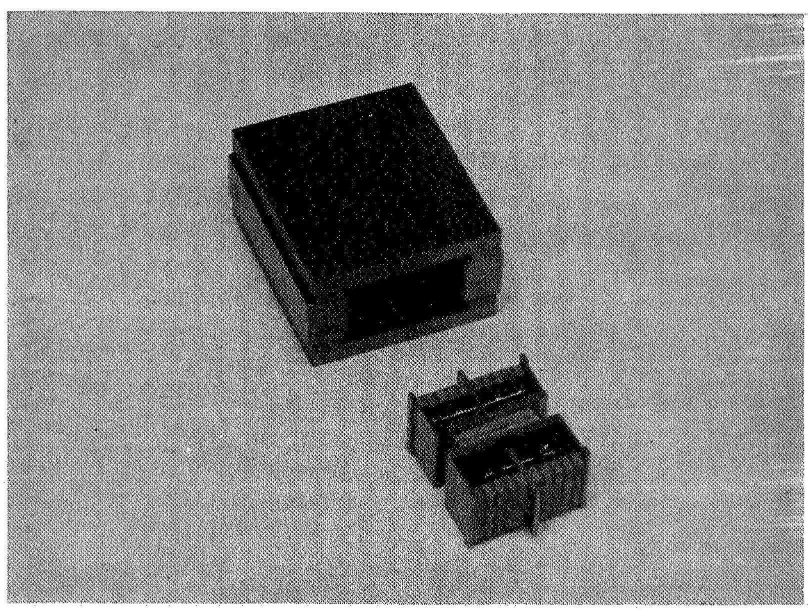


Figure 8. Assembled Clutch and Housing

To deal with these problems the invar was roughed in the area of the bond, the 0.770 dimension was reduced to 0.753, and the entire assembly operation was repeated and a 48 hour cure allowed.

Upon curing of the epoxy, the wires were attached to the piezoelectric elements, the clutch installed in the actuator housing and wires integrated into the control console. The clutch unit was successfully made to "walk" within the housing in forward and reverse directions on command. However, no force could be exerted by the actuator. Further operation and examination of the unit had indicated the reasons for this low force was a loose fit on one of the clutches and a marginal fit on the other.

The main problem area of the program had now been entered; that is the problem of controlling the size of the clutch unit to very close tolerances to match the housing built from gage blocks.

As the total motion on each clutch is theoretically set at 93×10^{-6} inches, for successful operation the clutch size must therefore be controlled to a small fraction of this motion. Work was started on a process of plating the clutch faces to build up its size to a correct dimension in a controlled manner.

In this method, a clutch produced slightly undersized is immersed in a laboratory plating bath to produce a buildup of nickel on the Invar clutch faces. By correct timing of the immersion in the bath microinches of plating can be obtained. The clutch is brought out periodically and tried in the housing. A D.C. voltage being applied to the clutch element for insertion and removed to prove the clutch grip.

This procedure was tried on the first clutch unit. Initial trouble was experienced with the plating procedure, however, a buildup of nickel was obtained on the clutch and a slightly improved fit of the clutch in the housing resulted. Since further experimentation with nickel plating produced very little progress, and since considerable preparation of the clutch face was required to obtain good adhesion and surface finish of the plating, a copper plating process was investigated.

An electroless copper plating bath was prepared and clutch No. 1 was immersed for plating. A total of three mils was required on each clutch face.

After two hours 1 mil of copper had deposited on each face and it appeared that very little more was accumulating. Since clutch No. 1 required excessive plating it was decided that it should be reassembled and was immersed in a solvent to disolve the cured epoxy.

Most subsequent experimentation with this form of plating resulted in very little progress, and it too was abandoned with clutch lapping remaining as the most favored technique.

In addition, it was felt that the clutch face supporting webs were excessively stiff and modification of these webs were performed as shown in Figure 9(PC072D0010A).

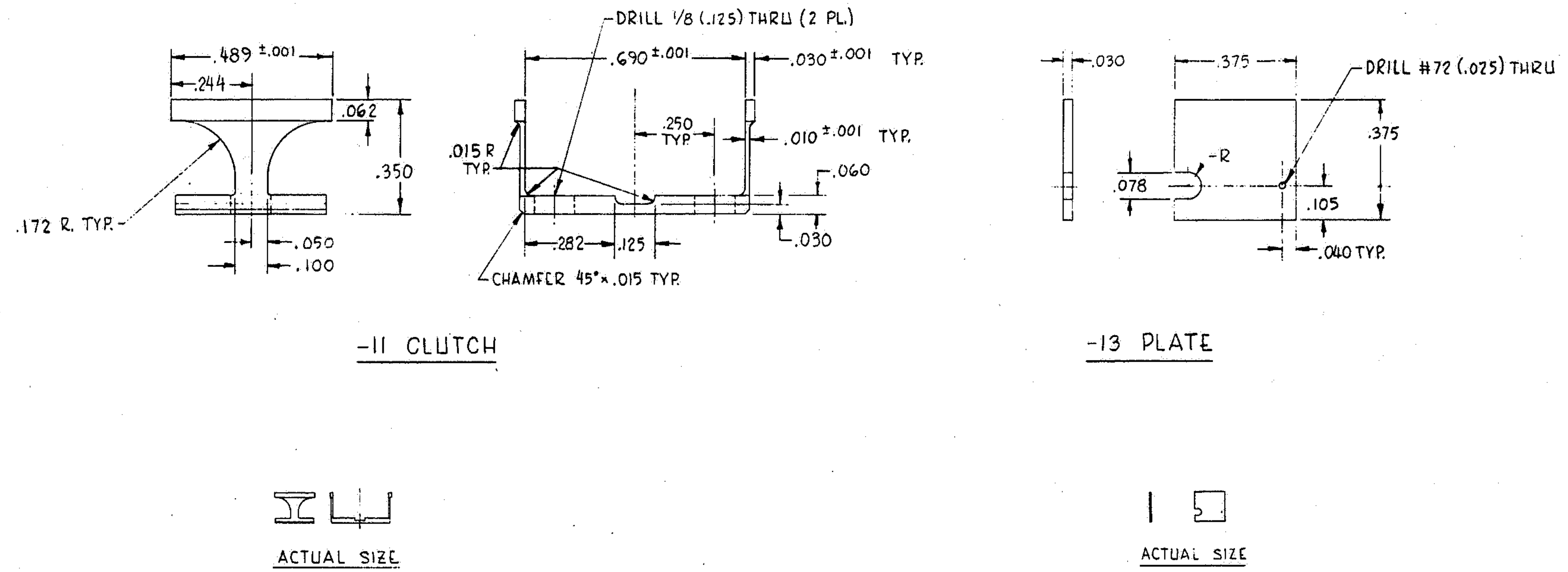
Once again a clutch assembly was completed, and after a slight amount of clutch face lapping, the assembly was successfully made to "walk" within the housing in forward and reverse directions on command. Virtually no force could be exerted by this clutch, all motion being stalled with very little force. One other assembly, however, when preloaded in the down direction was able to "walk" (in the down direction) as long as the 600 Hz excitation voltage was applied, when removed clutch motion ceases and the preload force supported. Since further lapping of the clutch faces would result in an undersized clutch assembly,it was decided to revise the actuator housing assembly procedure and build the housing around the finished clutch unit itself.

This choice of direction resulted in the first true realization of success. The clutch faces were hand lapped to a flatness of 10 microinches and parallel to within one second of arc. Upon completion of this task the next procedure was to build a housing to mate with the reworked clutch assembly. This was achieved by placing a gage block on both surfaces of the clutch faces and epoxying the side plates onto the gage blocks as shown in Figure 10. Since the particular clutch assembly that was used expands when excited by a positive 400 V signal, the procedure of assembly described above would permit relatively no clearance at zero volts when the clutch should be free of the walls. To alleviate this condition a 100 volt D. C. bias voltage was applied to the clutch elements expanding them one-fourth of their total growth. This provides approximately 24 millionths total clearance at zero volts or 12 millionths clearance on each side.

PC 072 D0010

TYPE OF CHANGE	EAI INC	REWORK PERMIT YES	REWORK PERMIT NO	SYM	DESCRIPTION	DATE	APPROVED
A							

REVISIONS



QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT
				-13		PLATE	.030	.4	.4		INVAR			
				PC072D0010-11		CLUTCH		.375	.52	.76	INVAR			

STOCK SIZE

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

NEXT ASSEMBLY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QUANTITY REQD	

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED

DEC TOL	SH MET. RAD
2 PLACE ±.	BEND:
3 PLACE ±.005	COR:
ANGULAR ±1/4°	DEBURR ALL EDGES

APPLICABLE SPECIFICATIONS

FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE

DO NOT SCALE DRAWING

DRAWN	J. VARGA	4-19-67
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STRUCT		
WEIGHTS		
PROJ ENGR		

CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

CLUTCH DETAIL - MICROACTUATOR

SIZE C | CODE IDENT NO. 77751 | PC 072 D0010 | A

SCALE 4 X | UNLESS OTHERWISE NOTED | SHEET 1 OF 1

PC 072 D0010 | 1

FIGURE 9

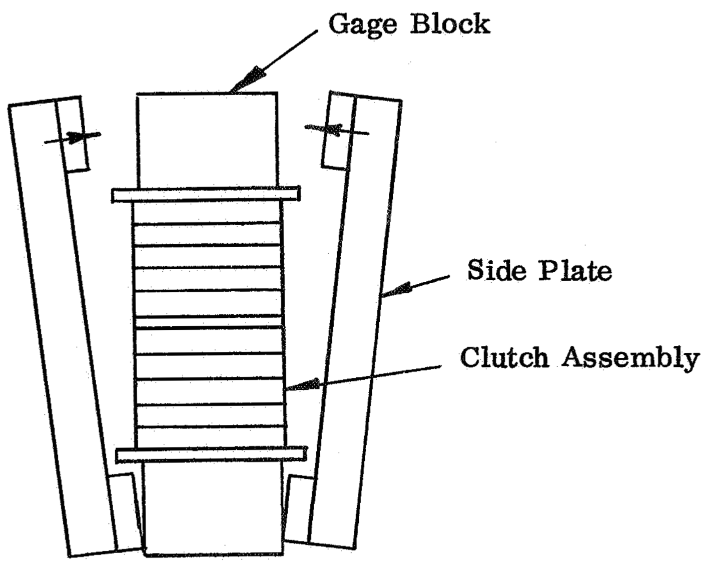


Figure 10. Actuator Housing Assembly

The housing was allowed to cure for 24 hours at which time the 100 V D. C. bias voltage was removed. The clutch assembly moved freely within the housing and when held vertical, would fall free. In order to establish whether the clutch would expand and support itself, a D. C. power supply was introduced and at 400 V D. C. there appeared to be adequate expansion, and the clutch assembly was capable of supporting a load in excess of 3 pounds.

At this time, an attempt was made to operate the clutch using the electronic control console. The clutch assembly was installed into the housing and appropriate electrical connections made. The driving signal of 400 V at 600 Hz was applied and the clutch was made to walk in the extend and retract direction on command. A series of weights were applied and it appeared as though the actuator would lift weights up to approximately 100 gms stalling out at 200 gms.

In an attempt to evaluate the actuator's performance at lower stepping rates than 600 cycles per second, a variable rate electronic driving circuit was designed and manufactured to permit operating rate to vary from 10 cycles per second up to 1000 cycles per second. The previously assembled successful actuator was integrated to the variable rate package and frequency was slowly decreased. Little performance improvement was noticed until the frequency was lowered below a few hundred cycles. Unquestionably, the performance at the lower frequencies appeared much more predictable than at the higher rates. Although the load carrying capability had not markedly increased, the consistency in motion per step improved, and overall performance established the feasibility of this type of actuator. Due to the trade-offs in rate, motion per step, total actuator volume, operating load, and others, it is suggested that perhaps operating specifications should be more closely examined if further development is pursued.

C. SECOND GENERATION ACTUATOR

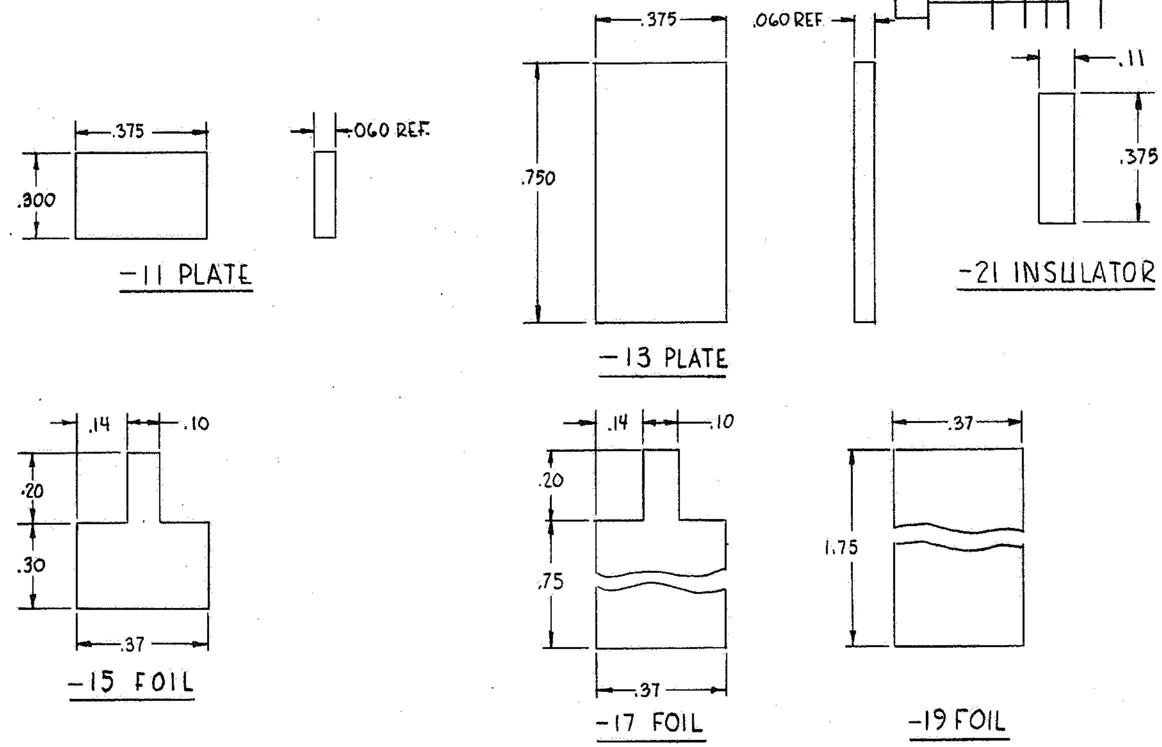
As a result of a positive amount of first generation actuator success, a more detailed study was undertaken to establish what factors determine successful operation of this design. Detailed structural analysis showed that the structural support members (webs) supporting the clutch face surfaces were deforming under the 1 kgm load one order in excess of the motion of the extender. Manufacture of further detail parts was stopped and based on information provided through this stress analysis a new design was derived.

Figures 11(PC072D0014), 12 (PC072D0015), 13 (PC072D0016) are the manufacturing drawings of the second generation actuator details with Figure 14 (PC072D0005) depicting the assembly.

As fabrication of the clutch elements became completed assembly of the second generation actuator progressed. Two stacks each consisting of six piezoelectric plates and five sheets of foil are required to complete one clutch assembly. Since the basic clutch assembly contains two clutches, four stacks were required. The clutch units were then epoxied on each side of the extender and the entire unit was allowed to cure for 48 hours. After precision lapping was completed the actuator housing was assembled around the completed clutch unit.

PC072D0014

TYPE OF CHANGE	EAI INC	REWORK PERMIT YES	REWORK PERMIT NO	SYM	REVISIONS DESCRIPTION	DATE	APPROVED



QUANTITY REQD						SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT
									-21		INSULATOR		.005	.2	.4	MYLAR SHEET .005 THICK			
									-19		FOIL		.002	.4	1.8				
									-17		FOIL		.002	.4	1.0				
									-15		FOIL		.002	.4	.6	} COPPER FOIL .002 THICK			
									-13		PLATE		.060	.4	.8				
									PC072 D0014 -11		PLATE		.060	.3	.4	} MAKE FROM PART NO. 56637 CLEVITE CORP., BEDFORD OHIO			

STOCK SIZE

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

NEXT ASSEMBLY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QUANTITY REQD	

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED

DEC TOL	SH MET. RAD
2 PLACE ±.01	BEND:
3 PLACE ±.005	COR:
ANGULAR ±	DEBURR ALL EDGES

APPLICABLE SPECIFICATIONS
FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE
DO NOT SCALE DRAWING

DRAWN	J. VARGA	11-27-67
CHECKED		
GR ENGR		
STRUCT		
WEIGHTS		
PROJ ENGR		

CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

PIEZOELECTRIC & FOIL DETAILS-
MICROACTUATOR

SIZE	CODE IDENT NO.	
C	77751	PC072 D0014

SCALE 4X UNLESS OTHERWISE NOTED SHEET 1 OF 1

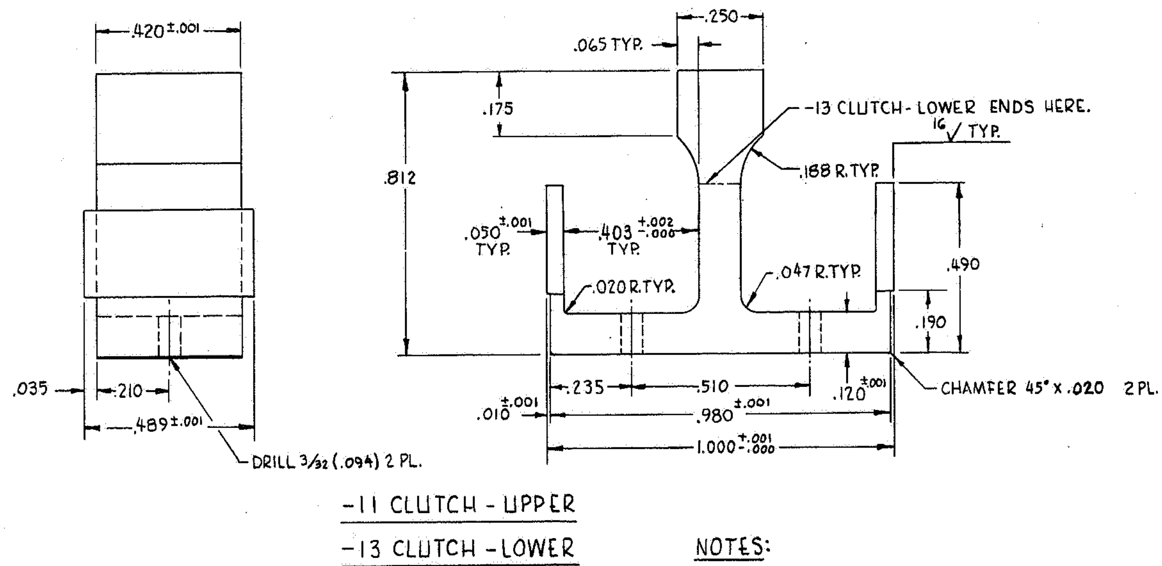
FORM RAD 141

PC072D0014

FIGURE 11

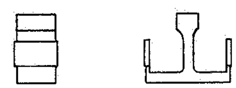
PC072D0015

TYPE OF CHANGE	EAI INC	REWORK PERMIT YES	REWORK PERMIT NO	SYM	REVISIONS DESCRIPTION	DATE	APPROVED



-11 CLUTCH - UPPER

-13 CLUTCH - LOWER



ACTUAL SIZE

NOTES:

1. REQUIREMENTS FOR MACHINED PARTS (UNLESS OTHERWISE SPECIFIED)

(A) MAX. RHR OF MACHINED SURFACES (EXCLUDING HOLES) 32 √ ALL OVER

(B) MAX. RHR OF HOLES TO BE PER SP900

(C) ALL FILLETS .005 R ± .003

(D) ALL EDGES TO BE ROUNDED .005 MAX.

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT
				-13		CLUTCH-LOWER		.5	1.1	.5	INVAR			
				PC072D0015-11		CLUTCH-UPPER		.5	1.1	.9	INVAR			

STOCK SIZE

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

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DIMENSIONS ARE IN INCHES UNLESS OTHERWISE NOTED

DEC TOL | SH MET. RAD
2 PLACE ± — | BEND:
3 PLACE ± .005 | COR:
ANGULAR ± | DEBURR ALL EDGES

APPLICABLE SPECIFICATIONS

FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE

DO NOT SCALE DRAWING

DRAWN J. VARGA 2-26-68
CHECKED
GR ENGR
STRUCT
WEIGHTS
PROJ ENGR

CONTRACT NO. NAS1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

CLUTCH DETAIL — MICROACTUATOR

SIZE C | CODE IDENT NO. 77751 | PC 072 D 0015

SCALE 4X UNLESS OTHERWISE NOTED | SHEET 1 OF 1

NEXT ASSEMBLY | USED ON — APPLICATION | NEXT ASSY | FINAL ASSY — QUANTITY REQD

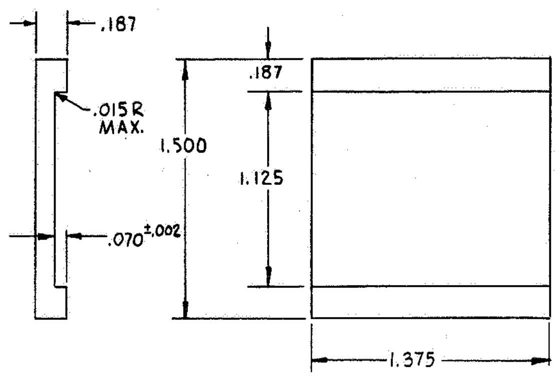
FORM RAD 141

PC072D0015

FIGURE 12

PC072D0016

TYPE OF CHANGE	EAI INC	REWORK PERMIT YES	REWORK PERMIT NO	SYM	REVISIONS DESCRIPTION	DATE	APPROVED



—11 PLATE

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT
				PC072 D0016-11		PLATE		.187	1.50	1.38	PRECISION GROUND FLAT STOCK	AISI TYPE O1		

STOCK SIZE

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

UNAUTHORIZED USE, MANUFACTURE OR REPRODUCTION IN WHOLE OR IN PART IS PROHIBITED. DRAWING, DESIGN AND OTHER DISCLOSURES PROPERTY OF FAIRCHILD HILLER CORPORATION.

NEXT ASSEMBLY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QUANTITY REQD	

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED

DEC TOL	SH MET. RAD
2 PLACE ±	BEND:
3 PLACE ±.005	COR:
ANGULAR ±	DEBURR ALL EDGES

APPLICABLE SPECIFICATIONS

FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE

DO NOT SCALE DRAWING

DRAWN	J. VARGA	3-7-68
CHECKED		
GR ENGR		
STRUCT		
WEIGHTS		
PROJ ENGR		

CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

HOUSING DETAIL-
MICROACTUATOR

SIZE	CODE IDENT NO.	
C	77751	PC 072 D 0016

SCALE 2X UNLESS OTHERWISE NOTED SHEET 1 OF 1

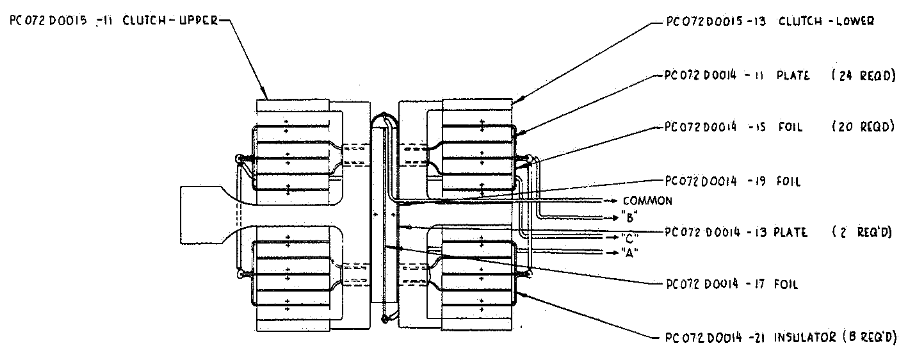
PC072D0016

FORM RAD 141

FIGURE 13

REVISIONS						
TYPE OF CHANGE	EAI INC	SEWORD PERMIT YES / NO	SYM	DESCRIPTION	DATE	APPROVED

PC072D0005



-1 CLUTCH ASSEMBLY

NOTES:

1. (+) INDICATES A NEGATIVE OUTPUT VOLTAGE UPON A COMPRESSIVE FORCE ON CERAMIC.
2. ASSEMBLE AS FOLLOWS:
   A. PREASSEMBLE 4 STACKS, EACH CONSISTING OF 6 PCS OF PC072D0014-11 PLATES & 5 PCS OF PC072D0014-15 FOILS. APPLY EPOXY TO BOTH SURFACES OF FOIL & BOTH SURFACES OF 4 CERAMIC PLATES AND ONE SURFACE OF 2 CERAMIC PLATES. ASSEMBLE EACH STACK NOTING BOTH POLARITY OF STACKS & POSITION OF FOIL TAB. CLAMP BETWEEN 2 STEEL PARALLEL BARS USING 2 .40000 INCH GAGE BLOCKS AS SPACERS. ALLOW TO CURE 24 HR. & REMOVE EXCESS EPOXY.
   B. ASSEMBLE 2 PIECES OF PC072D0014-13 PLATES WITH 1 PIECE OF PC072D0014-17 FOIL IN CENTER AND 1 PIECE OF PC072D0014-19 FOIL AS SHOWN & EPOXY AS "A" ABOVE.
   C. ASSEMBLE PC072D0015-11 & -13 CLUTCH ON EACH SIDE OF SUBASSEMBLY "B" ABOVE
   D. ASSEMBLE THE 4 STACKS (IN "A" ABOVE) INTO UPPER & LOWER CLUTCH SECTIONS. ATTACH WIRES AND ROUTE AS PER CONVIENCE.
   E. HAND LAP CLUTCH FACES TO FLATNESS LESS THAN 15 MICROINCHES RMS & PARALLEL TO 1/2 ARC SECOND.

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT
				#32 AWG		COPPER WIRE								
						DYNALOY 325 EPOXY					DYNALOY INC. NEWARK, N.J.			
				PC072D0014 -21		INSULATOR								
				-19		FOIL								
				-17		FOIL								
				-15		FOIL								
				-13		PLATE								
				PC072D0014 -11		PLATE								
				PC072D0015 -13		CLUTCH - LOWER								
				PC072D0015 -11		CLUTCH - UPPER								
-1				PC072D0005 -1		CLUTCH ASSY								
						ASSEMBLIES								

LIST OF MATERIAL

PART NUMBER MARKING PER MIL-STD-130

NEXT ASSEMBLY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QUANTITY REQD	

DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
DEC TOL | SH MET. RAD
2 PLACE ± | BEND:
3 PLACE ± | COR:
ANGULAR ± | DEBURR ALL EDGES
APPLICABLE SPECIFICATIONS
FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE
DO NOT SCALE DRAWING

DRAWN J. VARGA 4-12-68
CHECKED
GR ENGR
STRUCT
WEIGHTS
PROJ ENGR
CONTRACT NO. NAS 1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

CLUTCH ASSEMBLY—MICROACTUATOR

SIZE D | CODE IDENT NO. 77751 | PC 072 D 0005

SCALE 4X | UNLESS OTHERWISE NOTED | SHEET 1 OF 1

PC072D0005

FIGURE 14

The first actuator housing was allowed to cure with 100 volts D.C. bias being applied to the two clutches. This bias voltage contracts the clutch faces one-fourth of their total motion or approximately 29 microinches(14.5 microinches on each side of center). This provides an interference fit when the bias voltage is removed. After 24 hours of curing the clutch was integrated to the control console and the driving signal of 400 V at 60 Hz was applied. The clutch was made to walk in the extend and retract direction on command. A series of weights were applied and the actuator stalled out at approximately 100 gms.

This indicated that the interference fit, a function of the D.C. bias voltage applied during curing, was not large enough. As a result, housings were prepared with applied bias voltages of 150, 200, 250, 300, 350 and 375. In each case as bias voltage increased the load supporting limit increased. At an interference fit corresponding to a bias level of 300 volts D.C. the actuator was capable of raising a 500 gm weight. At the time of this writing performance at the 350 and 375 volt bias levels have not been confirmed.

A very important parameter which also affects the load supporting limit is the duty cycle of the clutches. Toward the end of this program some experimentation was performed and the results indicated that the less time the clutches are disengaged or contracted (when + 400 volt signal applied) the greater the load capability and the greater excursion per step. This is an extremely important parameter and should be investigated fully should any further development be pursued.

In addition some deflections have been measured between actuator housing walls, that is, the walls on which the clutches bear against, depending on whether the clutches are engaged or disengaged. This indicates that the load area between the gage blocks and the side plates of the housing is not adequate and should be at least doubled. Deflections in the order of 10 microinches maximum have been measured and although not excessive it still constitutes about 9% of total clutch excursion.

SECTION IV
ELECTRONIC CONTROL CONSOLE

A. CIRCUIT DESCRIPTION

The sequence of operation for the electrostrictive elements is described in Section II. This indicates that the actuator is operated by six voltage changes, in essence a charge and discharge cycle for each of the three elements. The basic control pulses to each of the piezoelectric elements, and their relationship to each other are shown in Figure 15.

Examination of these pulses reveals that the clutching operations can be controlled by a free running oscillator of a frequency equal to the rate of the actuator, 600 cps. A portion of the positive side of the oscillator waveform controls clutch B. The negative side of this waveform is inverted and a portion of this inverted waveform controls clutch C. The control for the extender is derived by selecting a portion of the initial waveform that is shifted in phase by 90°. The waveforms are clipped at a suitable voltage to give the "on-time" required for the sequence. To obtain a reversing of the actuator the control pulses for clutches B and C are simply reversed. The block diagram for this system is shown in Figure 16 . The length of "on-time" for each component can be varied by changing the clipping voltage level, the relationship of the extender pulse to the clutch pulses is varied by altering the phase shift. The pulses so far described are used as the control voltages to the bases of the driver amplifier transistors that apply the actuation voltage to the electrostrictive elements. The application of this voltage being programmed by the shape of the control pulse. The driver amplifier transistors are so biased as to be just in saturation at the maximum control pulse voltage. Thus providing a low impedance connection between the voltage supply and the elements.

Two electronic consoles have been designed and manufactured. The basic block diagram (Figure 16) remains the same for both however detail differences are enumerated below.

B. RACK MOUNTED CONSOLE

This console has been designed for standard 19.00 inch rack mount to facilitate possible stacking of additional consoles as the need arises. The front panel is

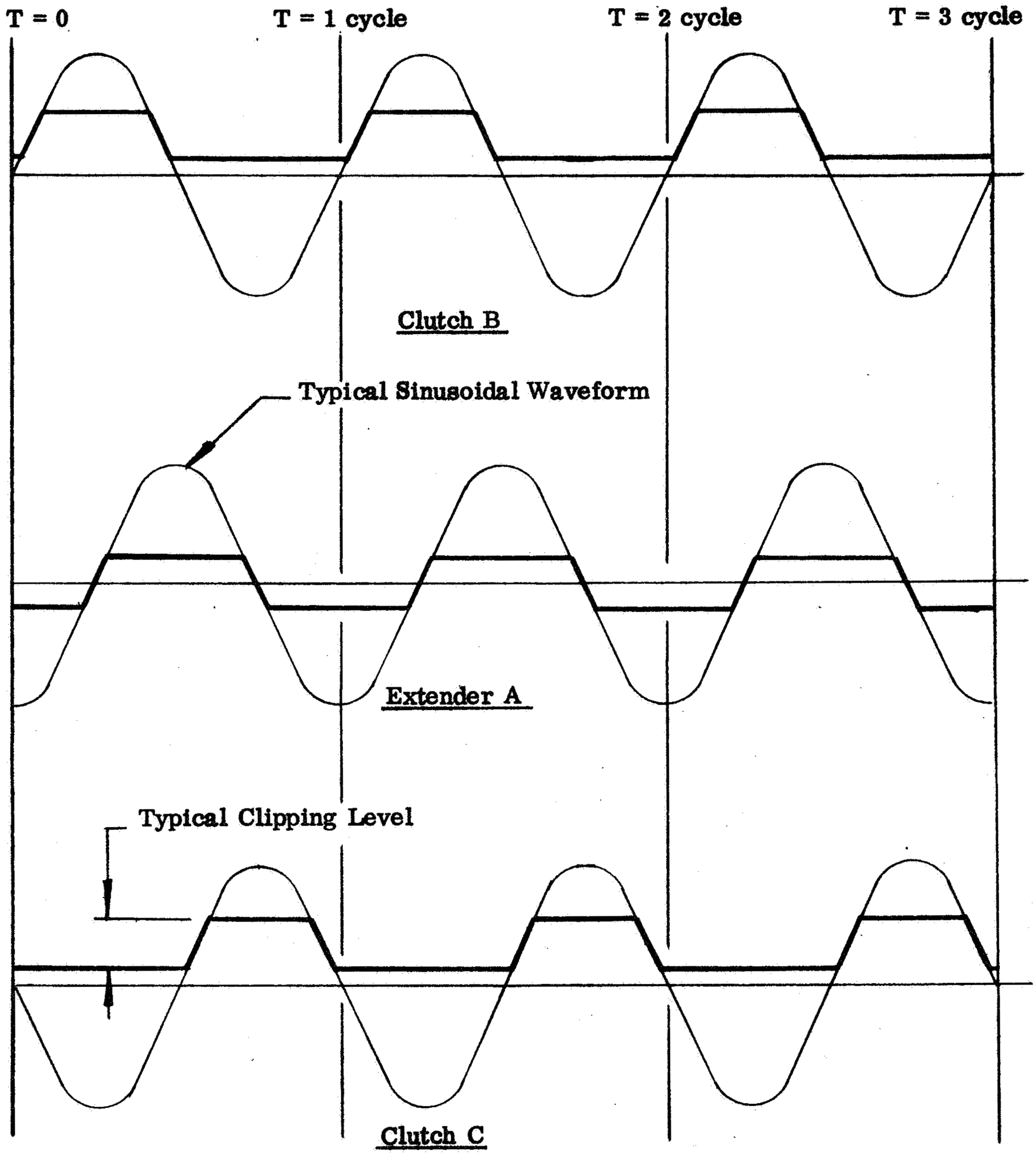


Figure 15. Control Pulses to Driver Amplifiers

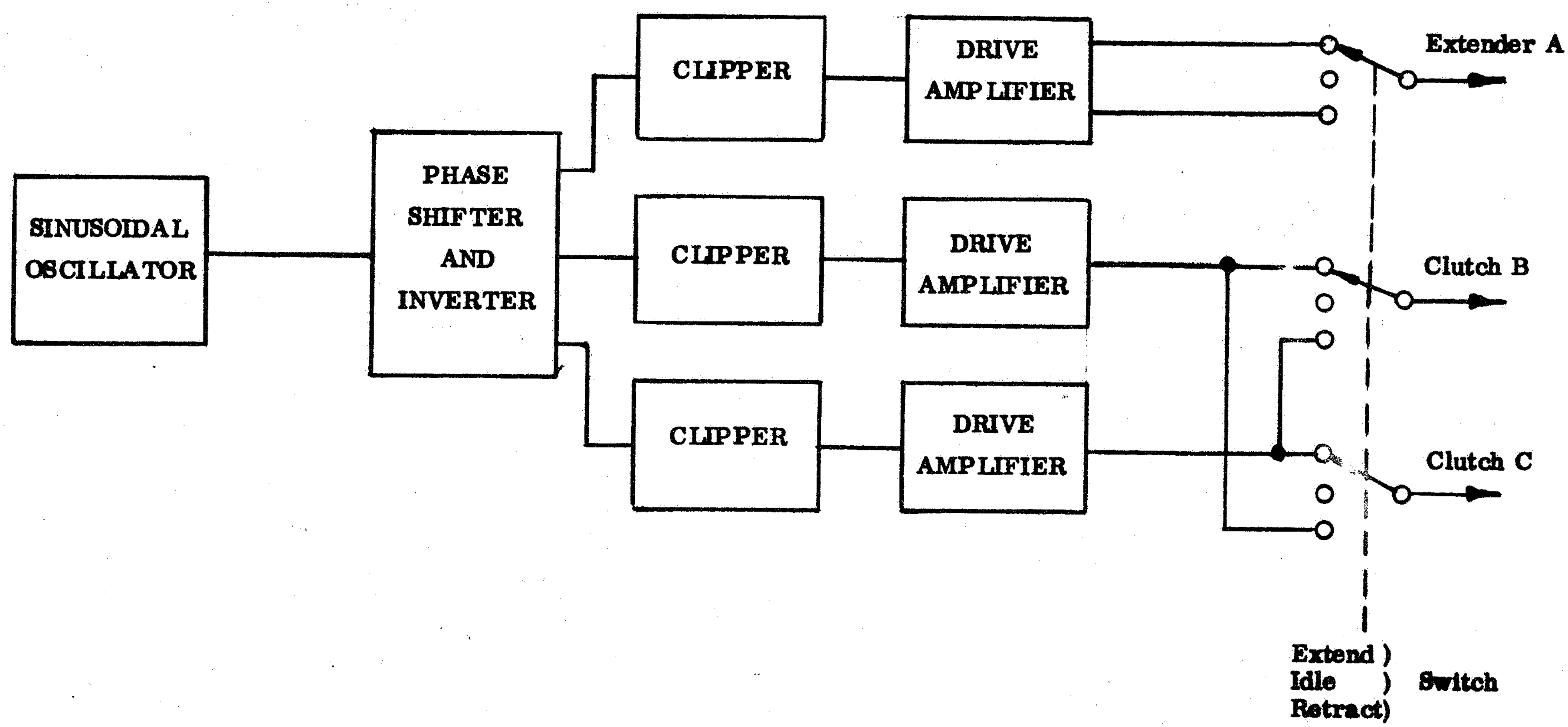


Figure 16. Control Circuit - Block Diagram

3.50 inches high and chassis dimensions are 17.00 inches wide, 3.00 inches high and 11.50 inches deep. Power Requirements are 117 volts A.C., 60 Hz at approximately 3/4 ampere. All front panel controls have been designated as depicted in Figure 17.

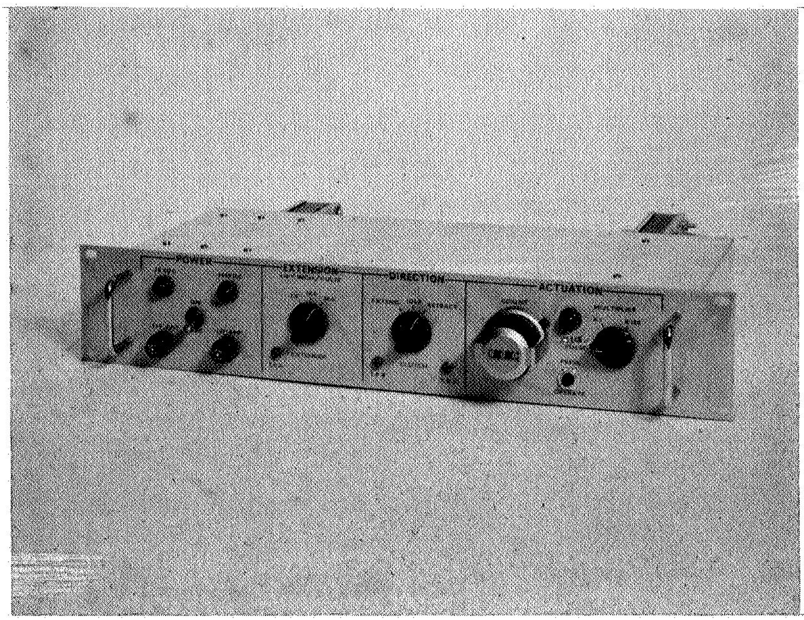


Figure 17. Front Panel Rack Mounted Console

Since solid state circuitry is used exclusively within the console, the use of preassembled circuit boards as opposed to open chassis wiring has been chosen.

Depicted in Figure 18 is the control console with the bottom removed. The function of the circuit boards from left to right is as follows:

1) Low voltage regulated power supply.
2) Sinusoidal 600 Hz oscillator with phase shift trigger amplifier.
3) Electronic switch and phase conditioning.
4) Clipper circuit.
5) Extender "A" driver amplifier.
6) Clutch "B" driver amplifier
7) Clutch "C" driver amplifier
8) Electronic timer.
9) Enabling logic.
10) High voltage regulated power supply.

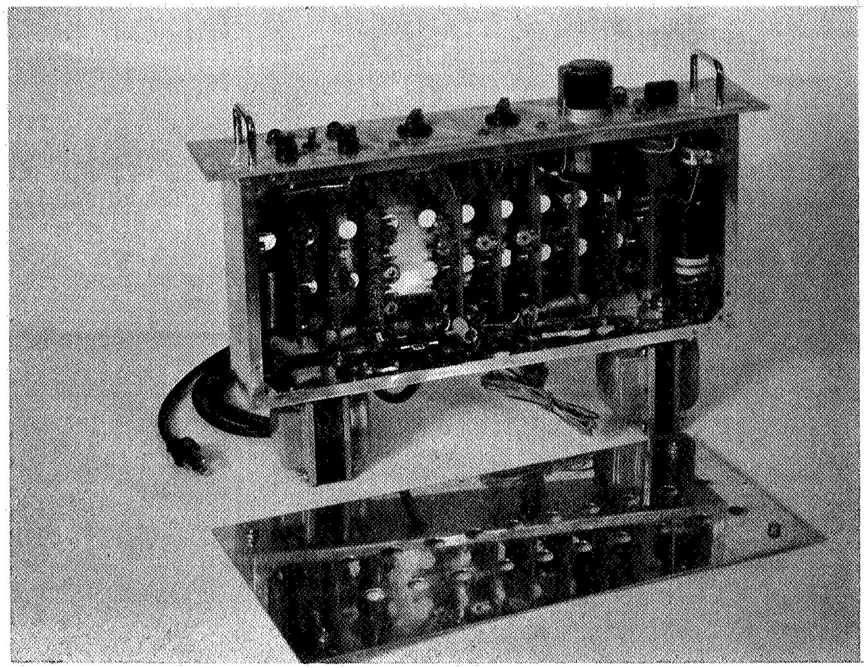


Figure 18 . Rack Mounted Chassis - Bottom Removed

Operation of this control console is as follows:

1) Turn A.C. power on and wait 1 minute for all transistor stages to acquire their proper bias levels.

2) Select desired extension per step. Since excursion per step is a function of load the control console has been calibrated in a no load condition.

3) Set direction switch to desired function, i.e. extend, idle or retract.

4) Set the actuation count ten turn potentiometer to desired setting for the total number of steps required as per calibration curve, Figure 19 .

5) Press operate button. While indicator light is lit, actuation is in progress.

6) Should only 10 cycles be required activate multiplier switch to "10 pulses."

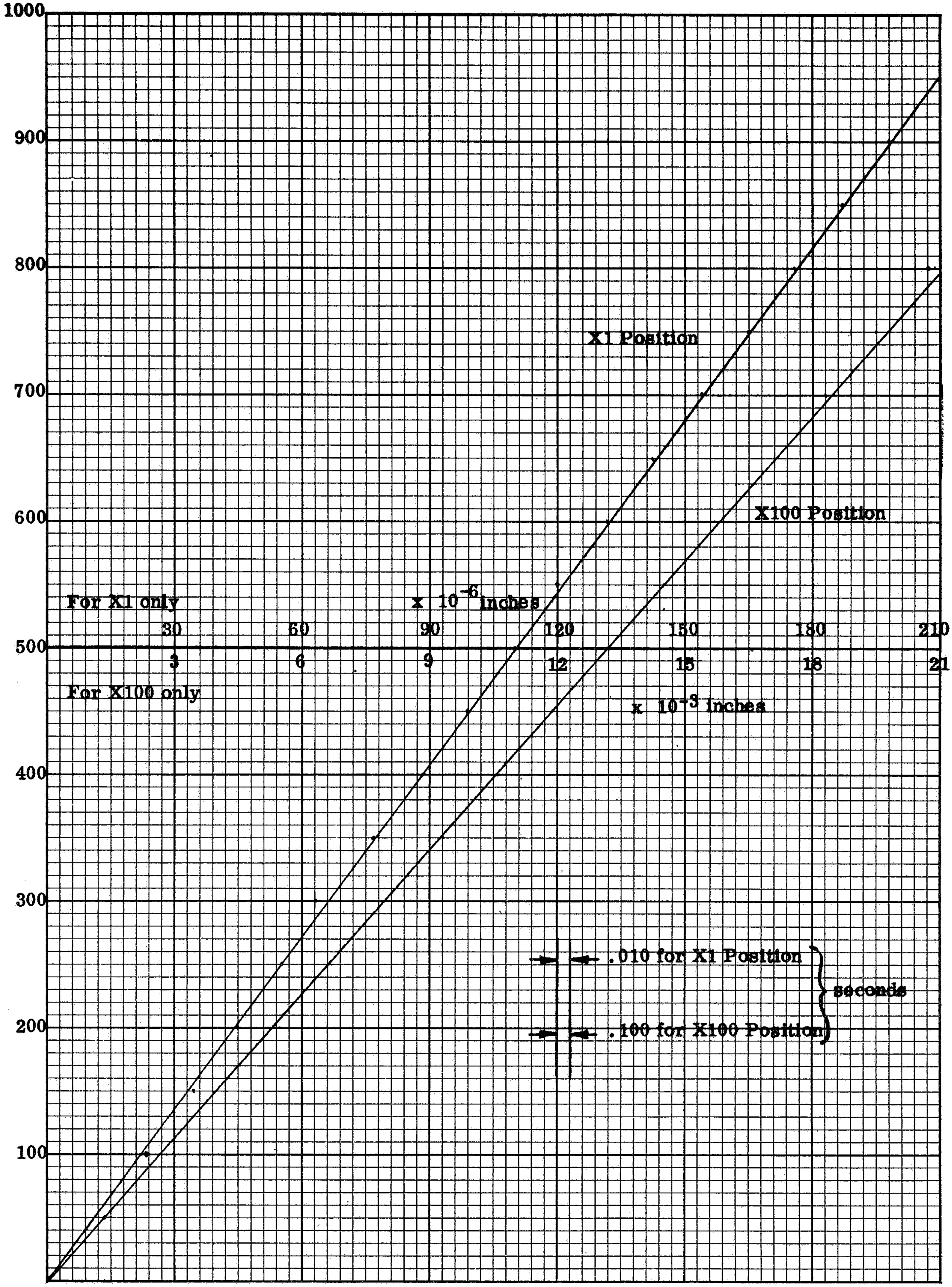


Figure 19. Calibration Curve - Count vs Excursion (no load)

Test points for oscilloscope viewing are supplied on the front panel with a scope synchronization output on the left side of the chassis. Test point outputs are 40 volts peak-peak and synchronization pulse is seven volts. Figure 20 shows phase shift and duty cycles of (top to bottom) extender, clutch B and clutch C.

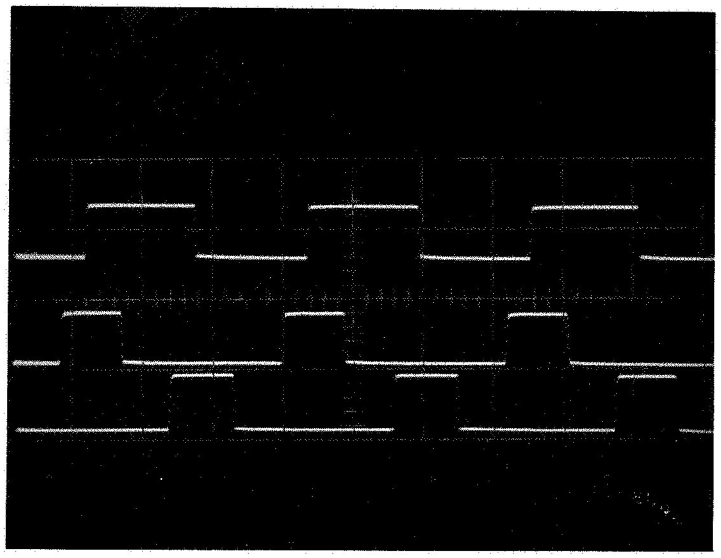
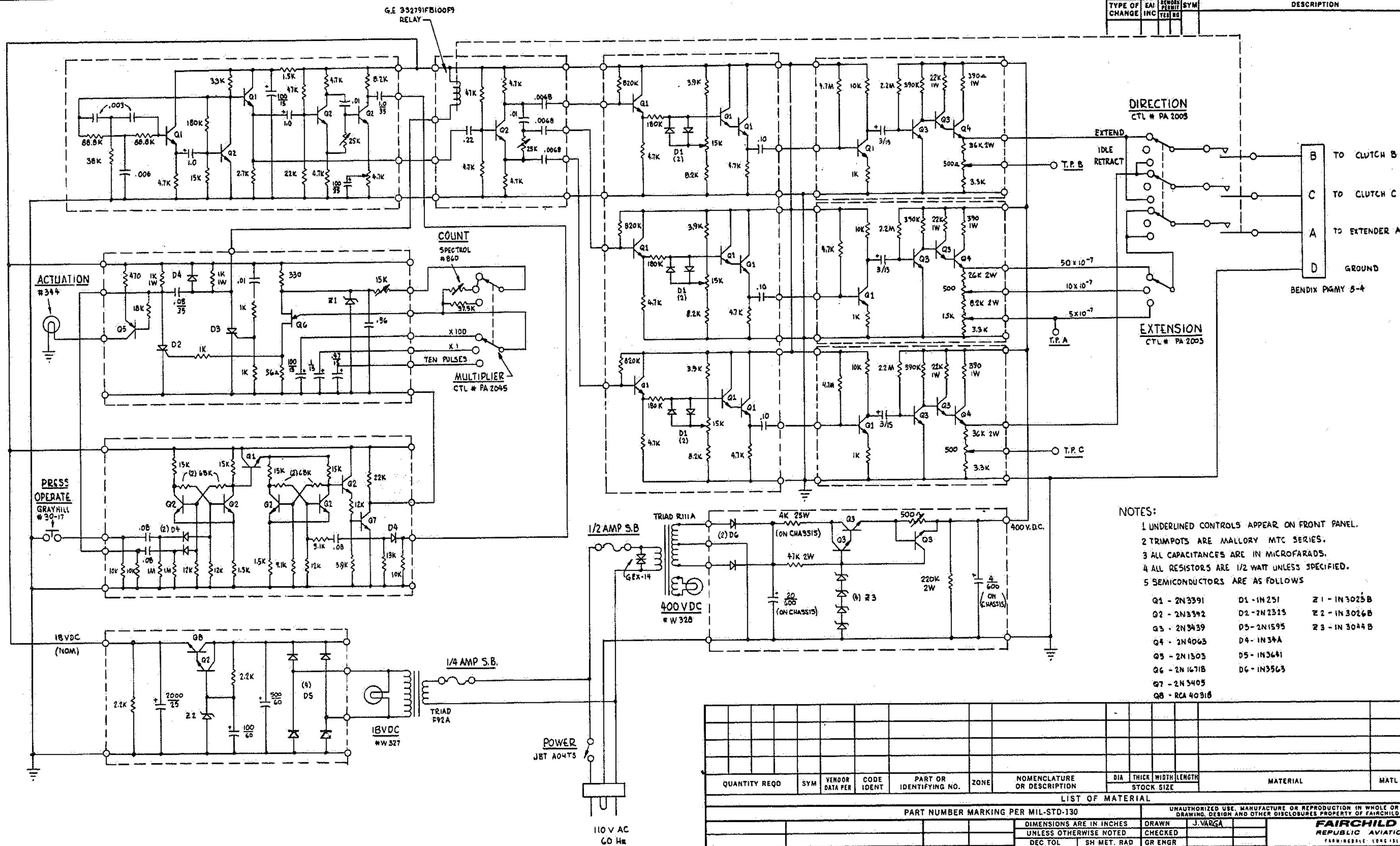


Figure 20. Waveforms of Extender, Clutch B and Clutch C

Figure 21 (PC072D0003) is the circuit schematic for the rack mounted console.

C. PORTABLE TABLE CONSOLE

Figure 22 shows the front view of the portable table console showing all front panel controls. This console has no timing circuit and as such is a much more compact unit. In addition it has the capability to apply a varying voltage onto the extender resulting in a variable extension or retraction excursion per pulse. The pulse rate of this package is fixed at line frequency or 60 Hz. As with the rack mounted console, a "warm-up" of approximately one or two minutes is required for coupling capacitors to assume their proper bias levels. This unit is activated by merely switching from idle to either extend or retract positions.



NOTES:

1. UNDERLINED CONTROLS APPEAR ON FRONT PANEL.
2. TRIMPOTS ARE MALLORY MTC SERIES.
3. ALL CAPACITANCES ARE IN MICROFARADS.
4. ALL RESISTORS ARE 1/2 WATT UNLESS SPECIFIED.
5. SEMICONDUCTORS ARE AS FOLLOWS

Q1 - 2N3391	D1 - IN251	Z1 - IN3025B
Q2 - 2N3392	D2 - 2N2325	Z2 - IN3026B
Q3 - 2N3439	D3 - 2N1595	Z3 - IN3044B
Q4 - 2N4063	D4 - IN34A	
Q5 - 2N1303	D5 - IN3641	
Q6 - 2N1671B	D6 - IN3563	
Q7 - 2N3405		
Q8 - RCA 40318		

REVISIONS

TYPE OF CHANGE	EAI INC	DEMOBS PERMIT YES NO	SYM	DESCRIPTION	DATE	APPROVED

LIST OF MATERIAL

QUANTITY REQD	SYM	VENDOR DATA PER	CODE IDENT	PART OR IDENTIFYING NO.	ZONE	NOMENCLATURE OR DESCRIPTION	DIA	THICK	WIDTH	LENGTH	MATERIAL	MATL SPECIFICATION	TS 1000 PSI	UNIT WT

STOCK SIZE

PART NUMBER MARKING PER MIL-STD-130

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DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE NOTED
DEC TOL | SH MET. RAD
2 PLACE ± | BEND:
3 PLACE ± | COR:
ANGULAR ± | DEBURR ALL EDGES
APPLICABLE SPECIFICATIONS
FINISH:
HEAT TREAT:
BEND RELIEF:
FOR ADDL SPEC SEE NOTE

DRAWN J. VARGA
CHECKED
GR ENGR
STRUCT
WEIGHTS
PROJ ENGR
CONTRACT NO. NAS1-7018

FAIRCHILD HILLER
REPUBLIC AVIATION DIVISION
FARMINGDALE, LONG ISLAND, NEW YORK

SCHEMATIC - RACK MOUNTED CONSOLE MICRO ACTUATOR

SIZE D | CODE IDENT NO 77751 | PC 072 D 0002

SCALE | UNLESS OTHERWISE NOTED | SHEET 1 OF 1

NEXT ASSEMBLY | USED ON | NEXT ASSY | FINAL ASSY
APPLICATION | QUANTITY REQD | DO NOT SCALE DRAWING

PC 072D0002

FIGURE 21

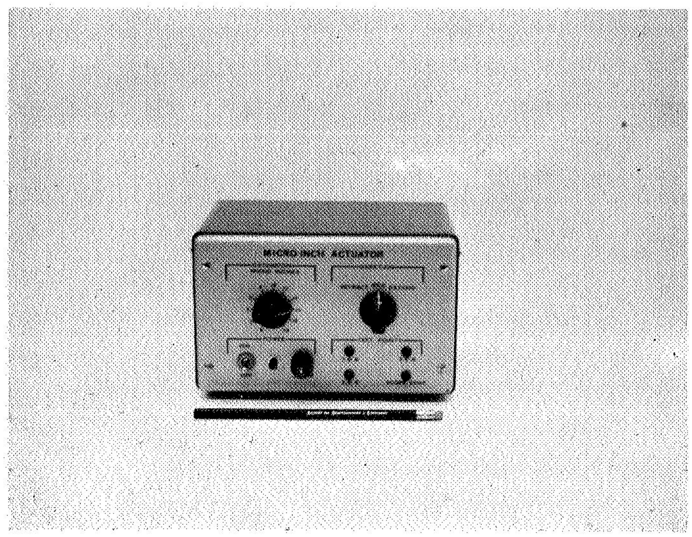


Figure 22. Front Panel - Portable Table Console

Figure 23 shows the phase shift and duty cycles of(top to bottom) extender, clutch B and clutch C. Depicted in Figure 24 (PC072D0002) is the circuit schematic for the portable table console.

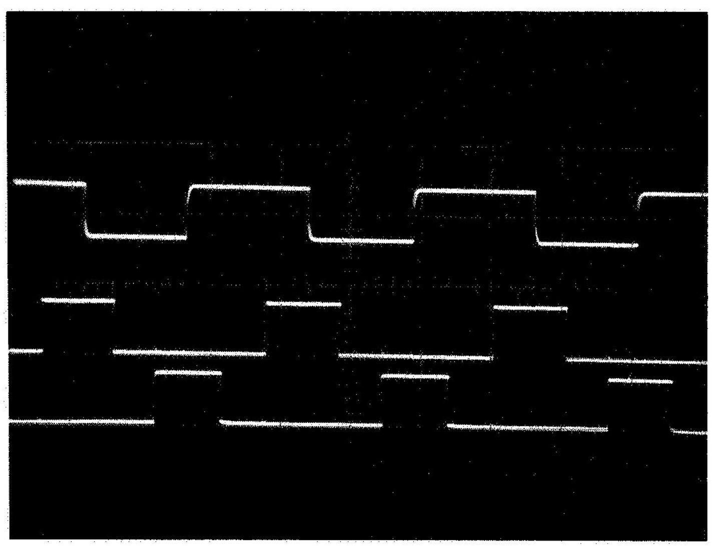
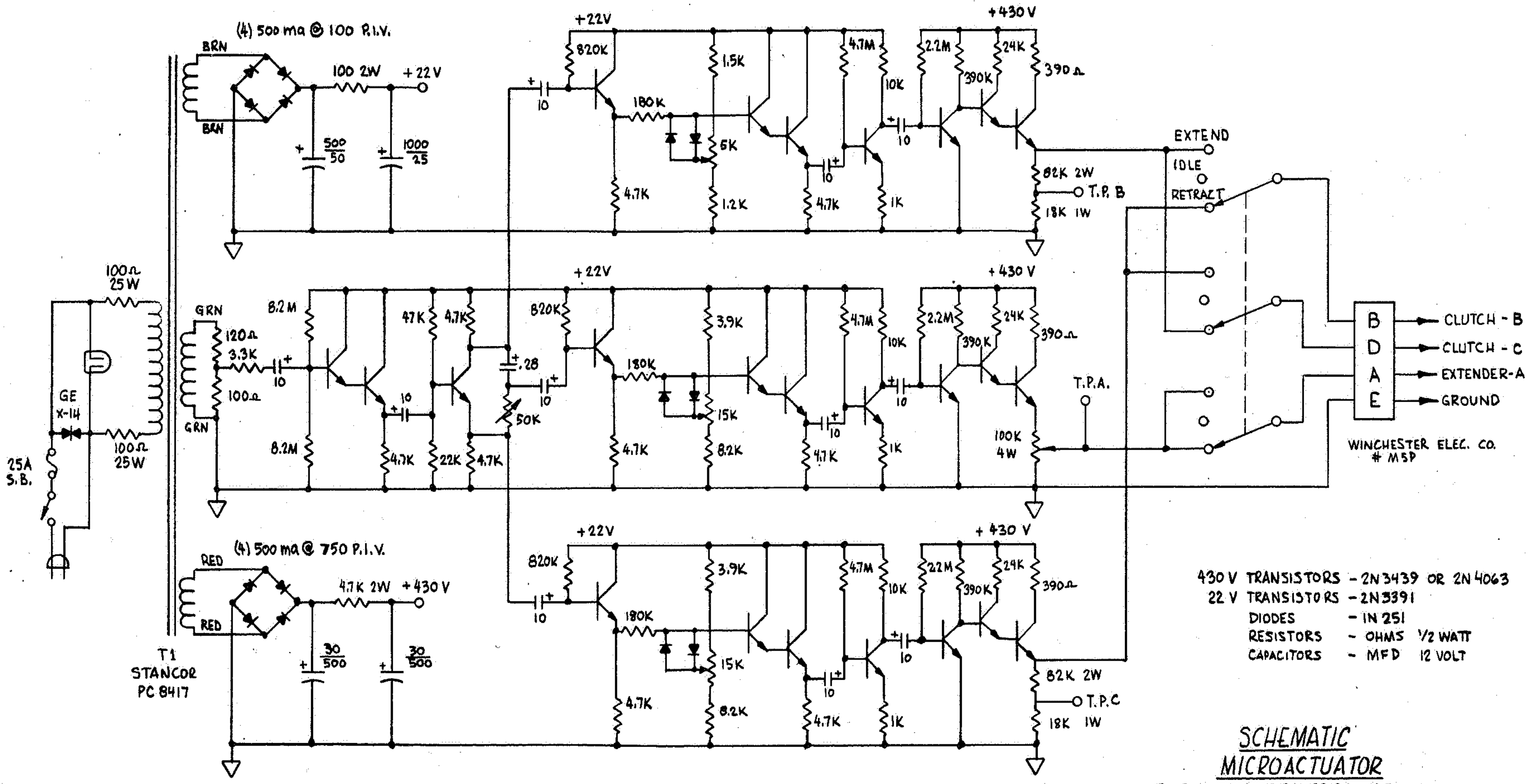


Figure 23. Waveforms of Extender, Clutch B and Clutch C



430 V TRANSISTORS	- 2N3439 OR 2N4063	
22 V TRANSISTORS	- 2N3391	
DIODES	- IN 251	
RESISTORS	- OHMS	1/2 WATT
CAPACITORS	- MFD	12 VOLT

SCHEMATIC
MICROACTUATOR
PORTABLE CONTROL CONSOLE

-FIGURE 24

SECTION V
PIEZOELECTRIC INVESTIGATIONS

At one point during the development of the first generation actuator it was decided to investigate the different ceramics available and perhaps different modes of motion in order to decrease the high amount of precision required for fabrication of the clutches.

Two basic directions were sought and are described below.

A. MONOLITHIC PIEZOCERAMIC STACKS

Gulton Industries, Metuchen, New Jersey, can manufacture monolithic piezoceramic stacks consisting of a large number (2 to 3 times the number presently used) of individual ceramic elements arranged mechanically in series and driven electrically in parallel. Since the "growth" per element is independent to thickness it was thought that this arrangement would yield larger total motions. In addition, the finished element is a solidly fused multiple layer device with only two surfaces to be bonded instead of the 14 presently required. This would have alleviated a percentage of the bond failures between foil and ceramic elements previously encountered. Figure 25 depicts an enlarged view of the monolithic piezoceramic stack and how it will be bonded in place.

After evaluation, it was learned that since 15 volts per mil was the maximum voltage level that could be placed across each ceramic element, the total excursion that could be realized for the existing volume was equal to that presently available. Furthermore, since this type of stack is a special item requiring long delivery times, the use of the material was abandoned.

B. BENDING MODE OF OPERATION

Investigation into various other modes of motion indicated that the bending mode of operation realizes the greatest motion. Figure 26 depicts an alternate design utilizing the bending mode. In order to establish feasibility of this mode a model actuator was assembled and is depicted full-size in Figure 27.

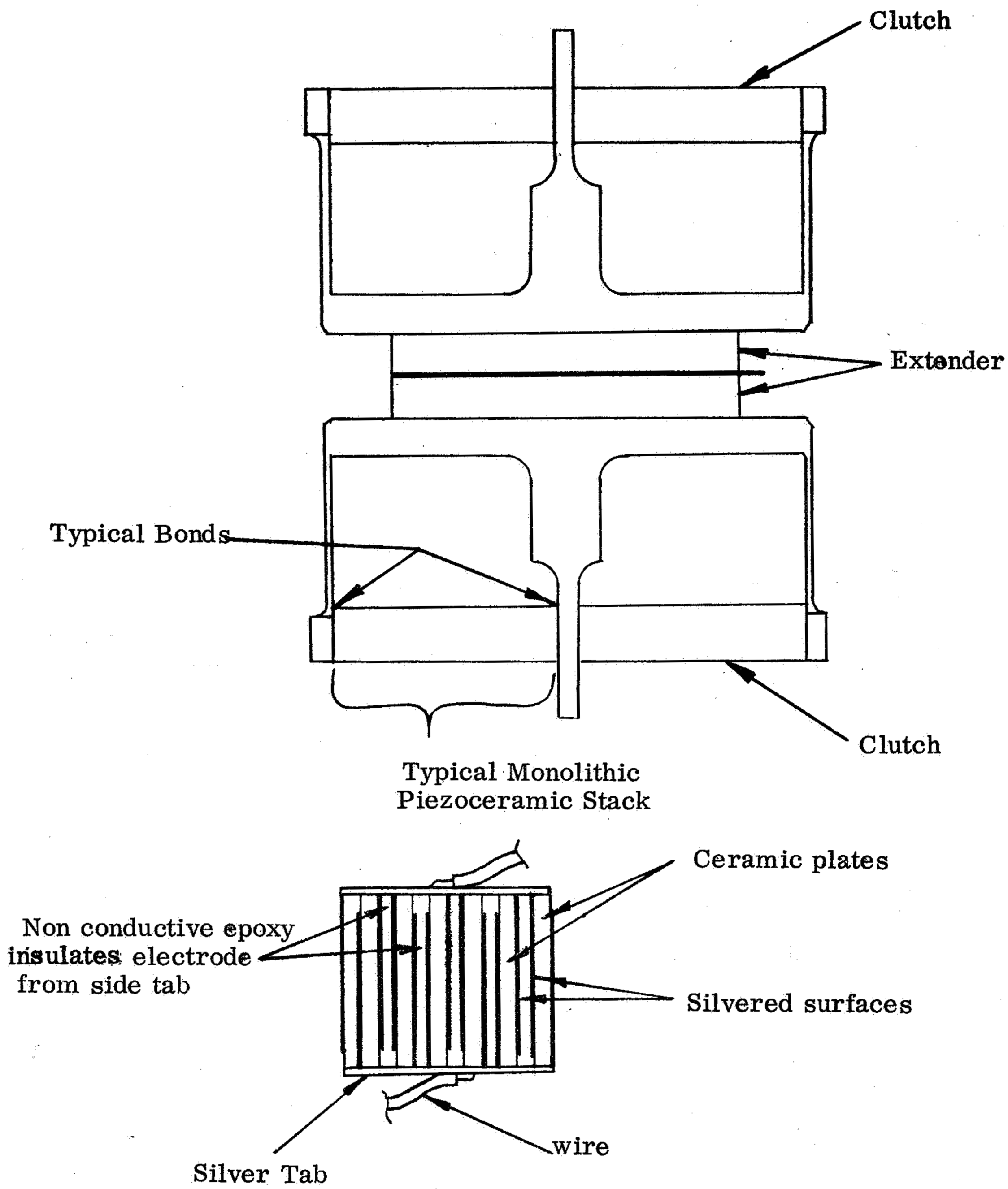


Figure 25. Clutch Assembly (4 times size)

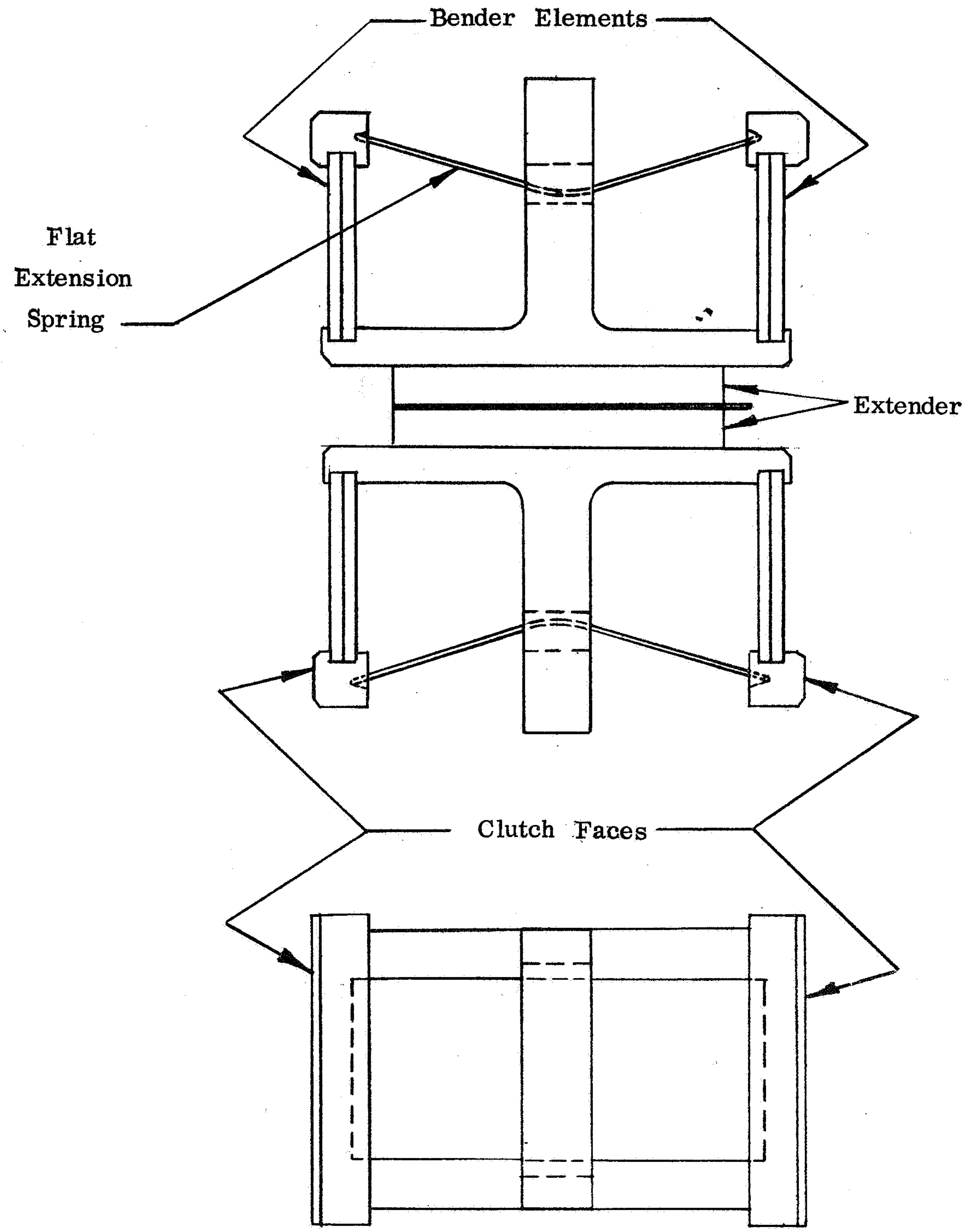


Figure 26. Bender Clutch Assembly (4 times size)

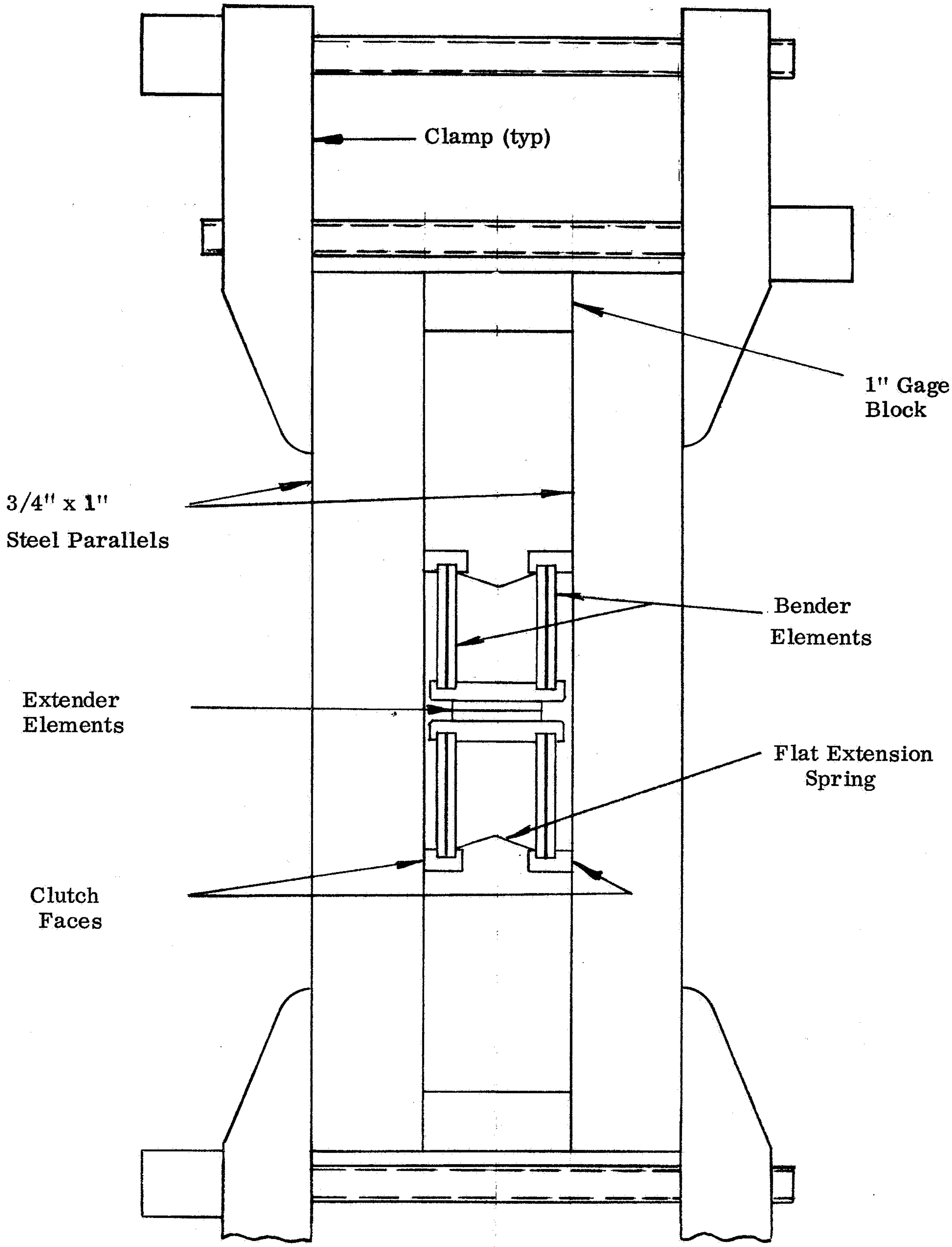
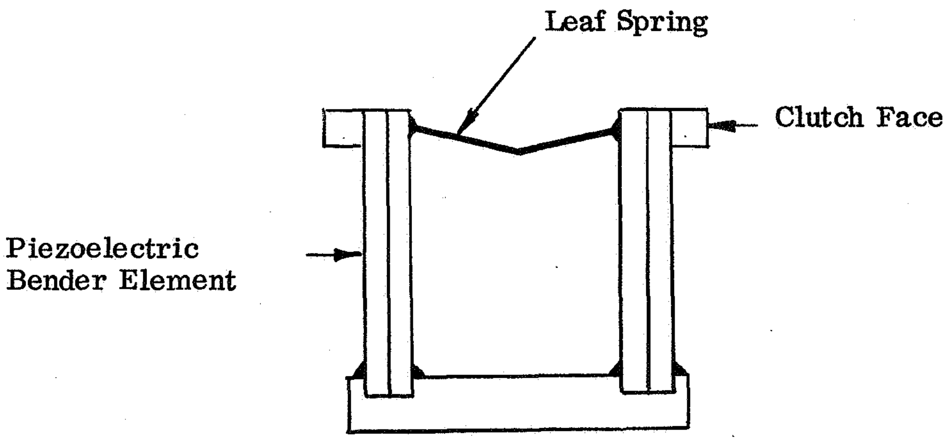


Figure 27. Model Actuator

Bending motions of the model actuator was calculated to be 500 x 10^{-6} inches each side of the wall or a total release of 0.001 inches. Static testing in the form of applying 400 volts D.C. to each bender element indicated deflections of 0.4 to 0.5 x 10^{-3} inches. In addition the completed clutch was inserted between the two 3/4" x 1" steel parallel and preloaded by adjusting clamp pressure so that the clutch would support 1 pound of axial force before slipping. At this point a 400 volt D.C. potential was applied to all bender elements and the clutch fell free indicating that complete release was occurring. However, when removing the D.C. potential the actuator could not support the initial 1 pound of axial force. The preload force was adjusted and the entire test was repeated, yielding the same result. A small leaf spring was manufactured and installed between both opposite pairs of clutch benders as illustrated below.



This arrangement, after tedious adjustment, was made to compensate for the previously experienced hysteresis effect, however, the actuator would no longer fall free upon application of the 400 V D.C. potential. In order to study this hysteresis and preload effect of the bender element with greater detail a small test setup was fabricated and is shown pictorially in Figure 28A and schematically in Figure 28B. Figures 29A and 29B depict a similar test setup used for investigating the characteristics of the extender element. Results of these tests indicate that although the bender elements produce more motion, its load capacity is lower. Conversely the stacked extender element, while the motion is smaller, its load capacity is greater yielding in both cases work that is generally equal.

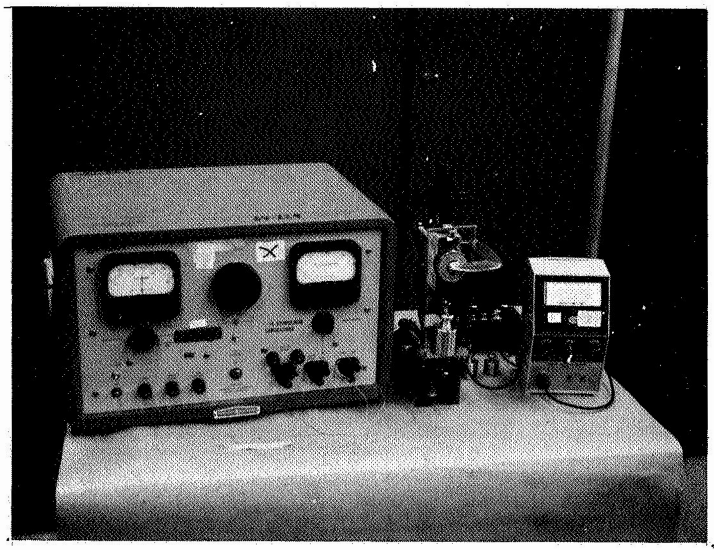


Figure 28A

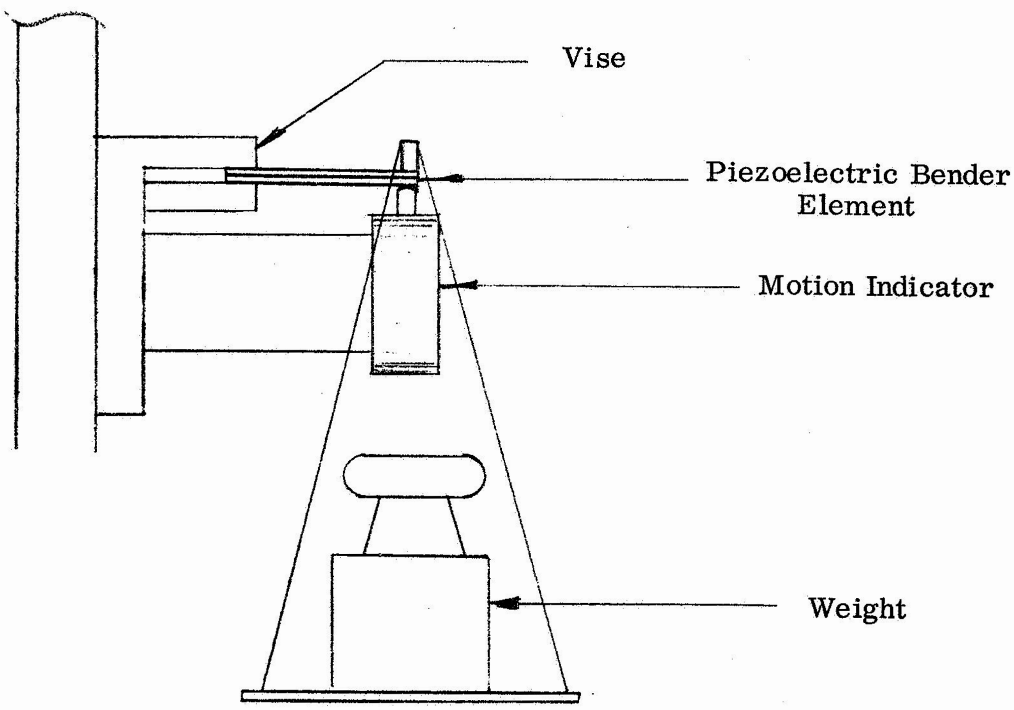


Figure 28B

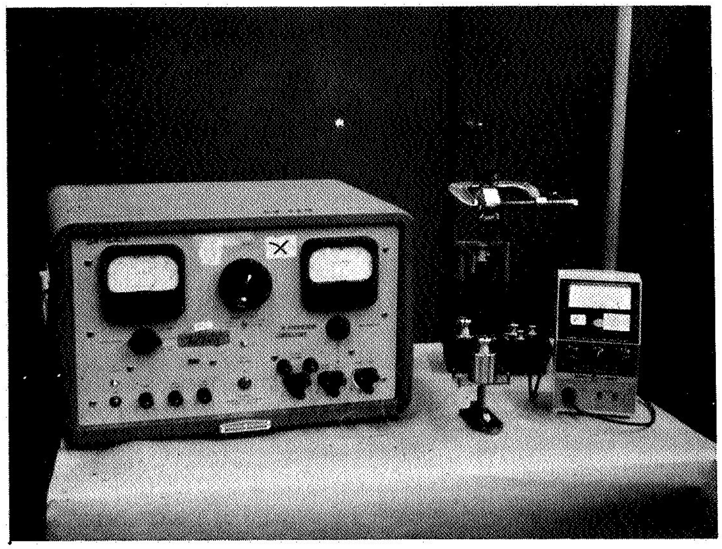


Figure 29A

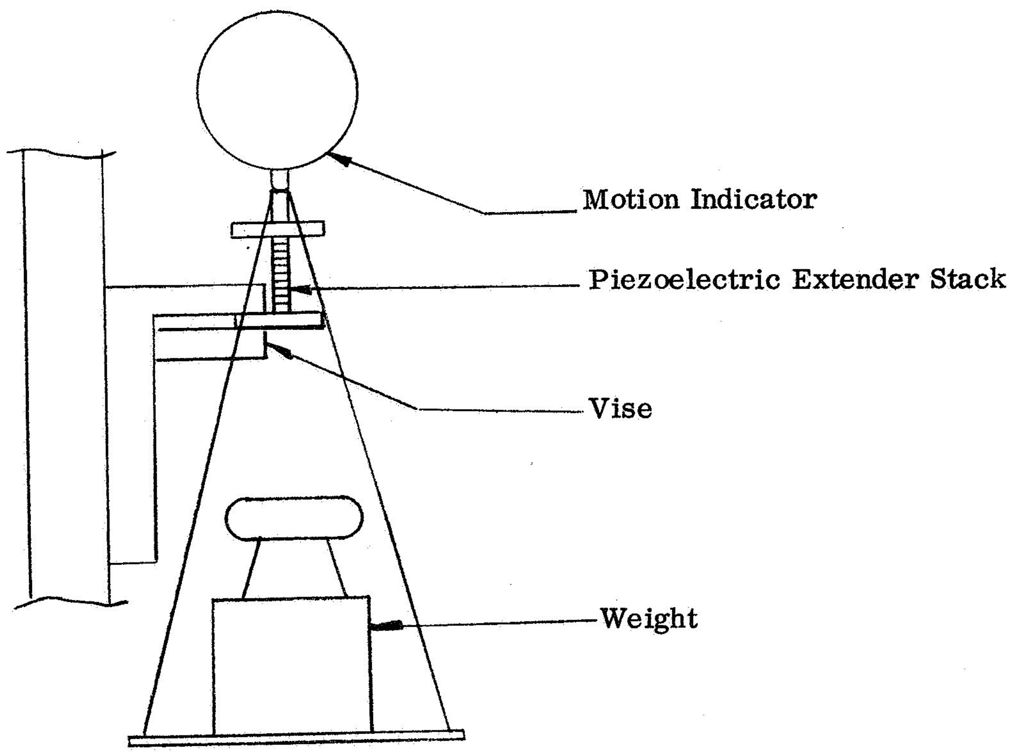


Figure 29 B

APPENDIX A
NATURAL OSCILLATIONS OF THE CLUTCH

In view of the fact that the clutch is a bounded elastic object and thus has finite strengths and dimensions it will have natural frequencies of oscillation. Indeed, these will be an infinitude of frequencies for each mode of wave propagation through the clutch. All of these natural or characteristic vibrations of the clutch will be excited when the clutch voltages are switched on and off during contraction and extension, respectively.

Although there are several infinitudes of frequencies to be considered in a complete analysis of the clutch motions, only one frequency will occur predominately. This mode of oscillation corresponds to compression waves being propagated parallel to the direction of extension and contraction of the clutch.

For a clutch length of 0.75 inch we determine the frequencies of the compressional mode of oscillation as follows. We assume that the center of the clutch remains fixed and that the ends vibrate (see Figure A-1)

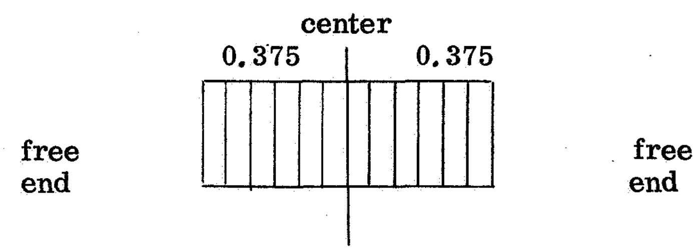


Figure A-1. Diagram of One Clutch

It can be shown by a detailed analysis of the vibrations of a bar with free ends, the displacement of the clutch is given by a sine function:

$$u(x,t) = e^{i\omega t} \sin kx$$

At the center $x=0$, the displacement is always zero. At the ends $x = \pm \ell$ the displacement is a maximum and hence we have the condition

$$\pm 1 = \sin k\ell - \sin(2n+1)\frac{\pi}{2} \qquad n = 0, 1, 2 \ldots\ldots, -1, -2, \ldots\ldots$$

The fundamental frequency (n = 0) is thus

$$k = \frac{\pi}{2\ell} = \frac{\omega}{c}$$

or $\omega = 2\pi f$ = frequency in radian

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \frac{\pi c}{2\ell} = \frac{c}{4\ell}$$

c = 4560 m/sec - velocity of compressional waves parallel to the polar axis for PZT-5H.

$\ell = \frac{1}{2} \times 0.75$ in. = 0.375 in.

$$f = \frac{4560 \text{ m/sec} \times 100 \text{ cm/m}}{4 \times 0.375 \text{ in.} \times 2.54 \text{ cm/in}} = \frac{4.56}{3.81} \times 10^5 \text{ cycles/sec} = \underline{120 \text{ KC}}$$

We note that the principal resonant frequency of the clutch, 120 KC, is well above, by factor of 120, the frequency of the voltages being applied to the clutch. Furthermore, all of the harmonic frequencies will be higher than 120 KC and also the frequencies generated by oscillations in the direction perpendicular to the polar axis are all higher than 120 KC because they are associated with smaller dimensions of the clutch. Hence their contribution can be neglected.

APPENDIX B

DYNAMICS OF CLUTCH AND EXTENDER

The object of this appendix is to calculate the amplitude of the crystal's resonant motion.

When clutch or extender are energized (or de-energized) the motion may be described by:

$$\frac{d^2x}{dt^2} + \omega^2 x = f(t) \qquad \text{(B-1)}$$

where

x	is the displacement
ω	is the natural mode of the crystal, rad/sec
$f(t)$	is the applied voltage waveform.

The frequency ω is the fundamental mode of longitudinal oscillations, given by

$$\omega = 2\pi f = (2\pi) \frac{c}{2\ell} \qquad \text{(B-2)}$$

with

c = velocity of compress. waves, 4560 met/sec

ℓ = length of crystal.

For the clutch (12 layers of 0.0625 in. material)

$\ell = 0.75$ in $= 1.90 \times 10^{-2}$ meters;

For the extender (2 layers of 0.0625 in. material)

$\ell = 0.125$ in. $= 0.316 \times 10^{-2}$ meters.

Thus the frequencies (in hertz) are:

<u>Clutch</u> $f = \dfrac{4560}{2(1.90)10^{-2}} = 120 \times 10^3$ Hz ; <u>Extender</u> $f = \dfrac{4560}{2(0.316)10^{-2}} = 722 \times 10^3$ Hz

The applied force has a wave shape as shown in Figure B-1.

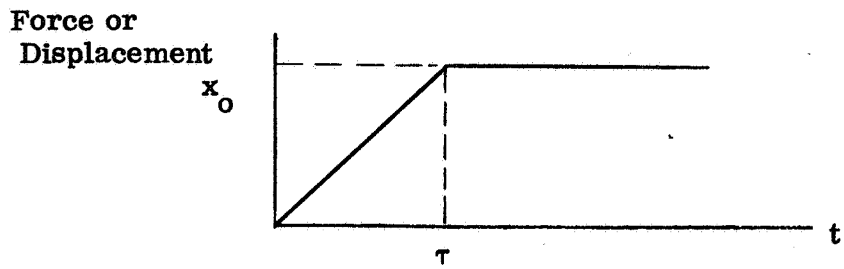


Figure B-1

In equation B-1, f(t) may be written as

$$\left.\begin{array}{ll} 0 < t < \tau & f(t) = x_o \omega^2 (t/\tau) \\ t > \tau & f(t) = \omega^2 x_o \end{array}\right\} \qquad \text{(B-3)}$$

This indicates a rise time of τ seconds, with an amplitude such as to cause a steady state displacement of x_o.

With the common notation for impulse, step, and ramp functions

$$\begin{array}{lll} \text{impulse at time t} & \rightarrow & S_o(t) \\ \text{step at time t} & \rightarrow & S_{-1}(t) \\ \text{ramp at time t} & \rightarrow & S_{-2}(t) \end{array}$$

Equations B-1 and B-3 may be combined as:

$$\frac{d^2x}{dt^2} + \omega^2 x = \frac{\omega^2 x_o}{\tau} \left[S_{-2}(t) - S_{-2}(t - \tau) \right] \qquad \text{(B-4)}$$

Solving by Laplace transforms:

$$(s^2 + \omega^2)\ X(s) = \frac{\omega^2 x_o}{\tau} \frac{1}{s^2} (1 - e^{-\tau s}) \qquad \text{(B-5)}$$

$$X(s) = \frac{\omega^2 x_o}{\tau} \frac{1 - e^{-\tau s}}{s^2(s^2 + \omega^2)}$$

$$= \left(\frac{\omega^2 x_o}{\tau} \right) \frac{1}{\omega^2} \left(\frac{1}{s^2} - \frac{1}{s^2 + \omega^2} \right) \left(1 - e^{-\tau s} \right)$$

Hence

$$x(t) = \frac{x_o}{\tau}\left\{S_{-2}(t) - S_{-2}(t-\tau) - \left(\frac{1}{\omega}\sin\omega t\right)S_{-1}(t) + \left[\frac{1}{\omega}\sin\omega(t-\tau)\right]S_{-1}(t-\tau)\right\} \qquad \text{(B-6)}$$

In more conventional terms B-6 may be expressed as

$$0 < t < \tau \qquad x = \frac{x_o}{\tau}\left(t - \frac{1}{\omega}\sin\omega t\right) \qquad \text{(B-7a)}$$

$$t > \tau \qquad x = \frac{x_o}{\tau}\left[\tau - \frac{1}{\omega}(\sin\omega t - \sin(\omega t - \omega\tau))\right] \qquad \text{(B-7b)}$$

or

$$0 < t < \tau \qquad x = x_o\left[\frac{t}{\tau} - \frac{\sin\omega t}{\omega\tau}\right] \qquad \text{(B-8a)}$$

$$t > \tau \qquad x = x_o\left[1 - \frac{2\sin(\omega\tau/2)}{\omega\tau}\cos\omega\left(t - \frac{\tau}{2}\right)\right] \qquad \text{(B-8b)}$$

Typically, the rise time τ might be 70 microseconds. In that case the amplitude of the oscillatory part of the response may be calculated from equation B-8b.

For the clutch ($\omega = 2\pi(0.12)10^6$)

$$\frac{\omega\tau}{2} = \frac{1}{2}\left[2\pi(0.12)10^6\right]\left[70 \quad 10^{-6}\right] = 26 \text{ radians.}$$

Since 26 radians $>> 2\pi$ the term $\sin\frac{\omega\tau}{2}$ may be any value between -1 and +1, depending on the exact value of $\frac{\omega\tau}{2}$. (The value 26 is an approximation, a few percent variation would cause large changes in $\sin\frac{\omega\tau}{2}$.) However, the total amplitude of the oscillatory term cannot exceed

$$\frac{2}{\omega\tau} = \frac{1}{26} = 0.0385.$$

Thus the static displacement is accompanied by a self-resonant oscillation of less than 3% of the static motion.

For the extender ($\omega = 2\pi (0.72)10^6$)

$$\frac{\omega T}{2} = \frac{1}{2} [2\pi (0.72)10^6] \; 70 \; 10^{-6} = 158 \text{ radians.}$$

With similar reasoning one concludes that the extender operation may have $\frac{1}{158}$ or 0.63% oscillation.

APPENDIX C
STATIC DESIGN

The actuator is illustrated schematically on Figure C-1. Figure C-2 shows the sequence of operation, the six phases of each step in the motion. Thus, in order to move the load up one unit the following operations are required:

1) Starting Position: extender in contracted state, upper clutch free and lower clutch engaged, the load being supported by the lower clutch.

2) Expand the extender, moving load up.

3) Engage Upper Clutch: (Both clutches are engaged, but the load will still be supported by the lower clutch).

4) Release Lower Clutch: (The load is now supported by the upper clutch).

5) Contract the Extender.

6) Engage Lower Clutch: (Both clutches engaged, but the load is still supported by the upper clutch).

7) Release Upper Clutch: (Load transferred to lower clutch).
or
1) Cycle Repeats

A similar sequence would apply for motion in the opposite direction. Note that the cycle described "raises" the load by the amount of the extender motion, minus a small amount of "lost motion" due to the load transfer from lower to upper clutch, and again from the upper to the lower.

This "lost motion" will now be analyzed to determine design dimensions for the actuator. Thus: Let Δ_E be the extender motion, per step. Figure C-3 indicates in an exaggerated fashion the deflection of the actuator under load. It is assumed that the central structure ("column" and "base," -Figure C-1) may be made exceedingly rigid, but that the "cantilever spring" and the "extender" be somewhat compliant. In phases (1), (2), and (3) with the load borne by the lower clutch the load "sags"

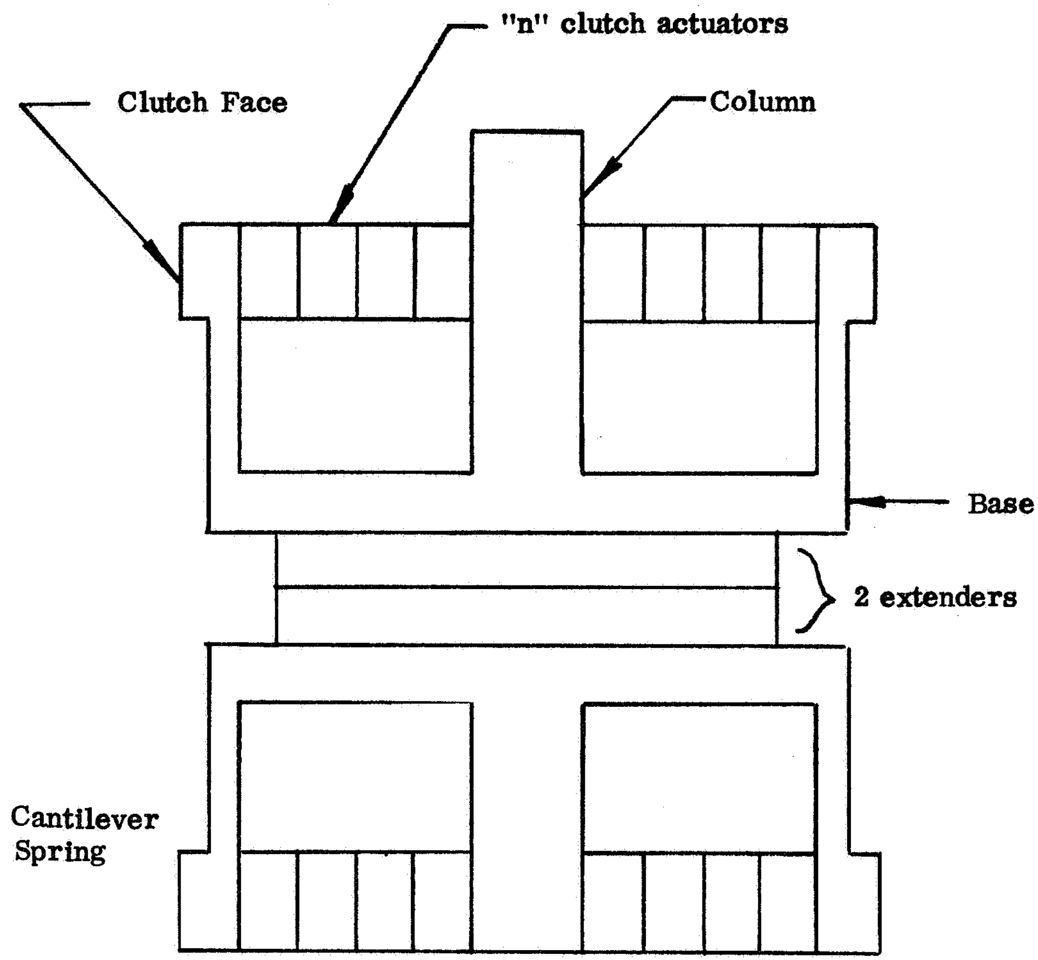
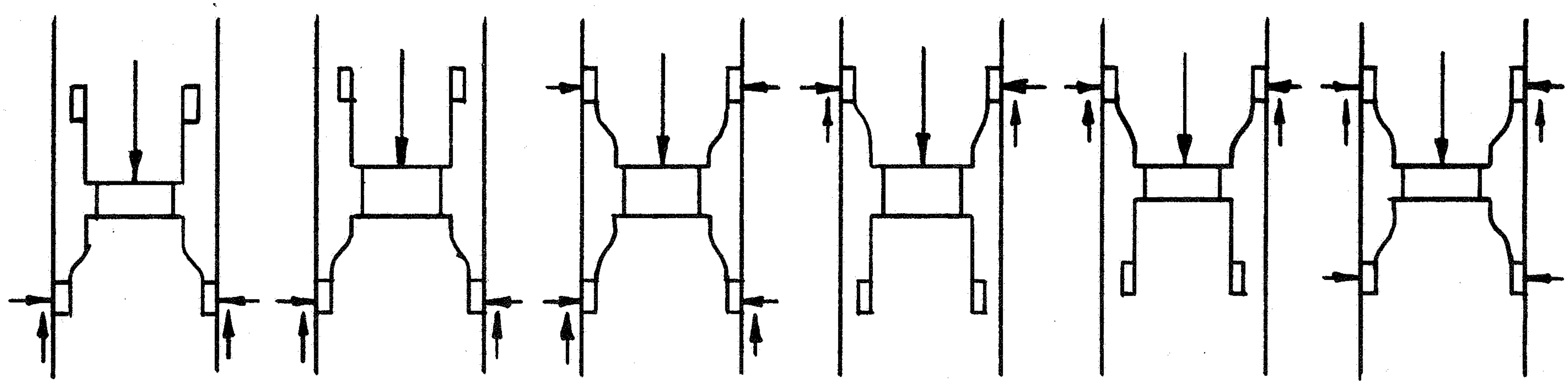


Figure C-1. Actuator Construction



	(1)	(2)	(3)	(4)	(5)	(6)
Upper Clutch	Free	Free	Engaged	Engaged	Engaged	Engaged
Lower Clutch	Engaged	Engaged	Engaged	Free	Free	Engaged
Extender:	Contracted	Expanded	Expanded	Expanded	Contracted	Contracted

Figure C-2. Sequence Schematic

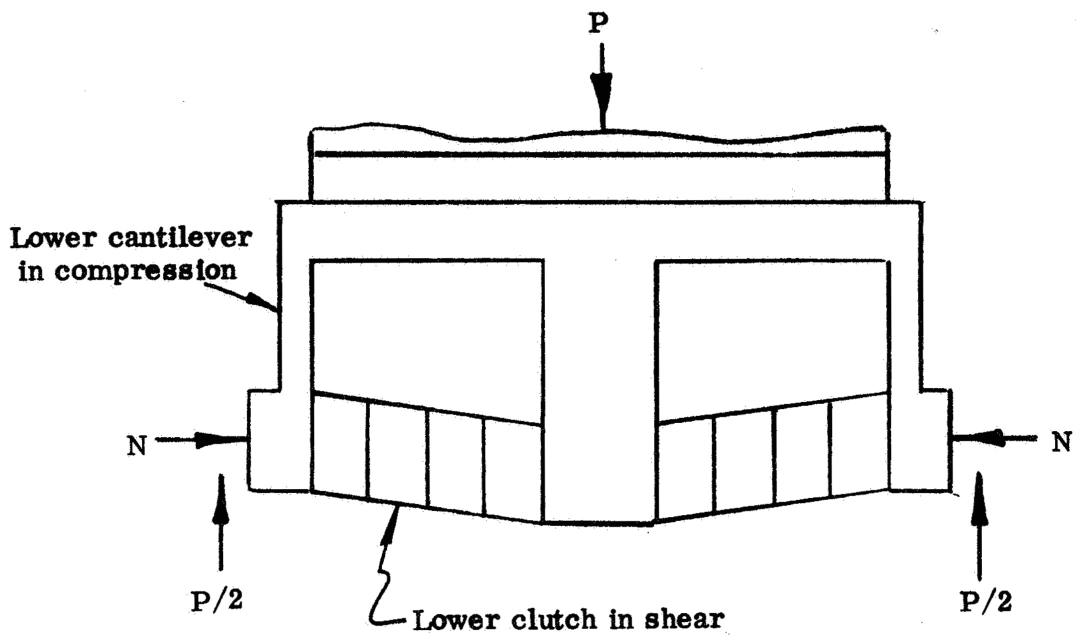


Figure C-3a. Steps 1, 2, and 3

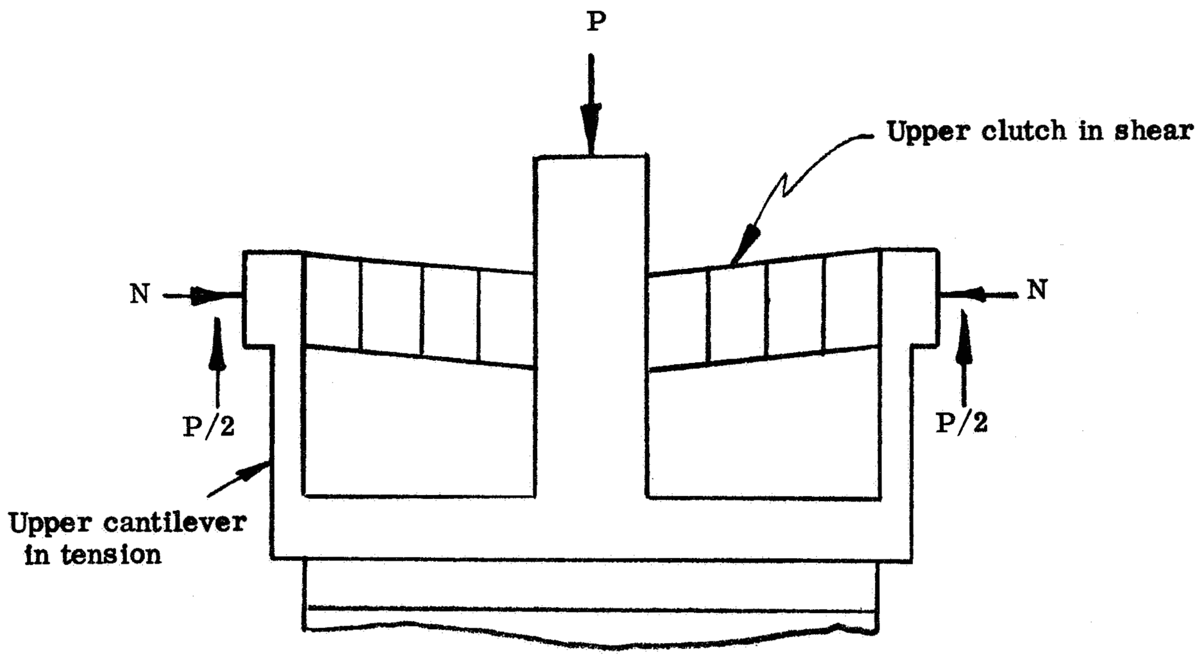


Figure C-3b. Steps 4, 5, and 6

by an amount Δ_L. In phases (4), (5), and (6) the load is borne by the upper clutch and an additional sag Δ_U develops. Thus during the six phase cycle the load is pushed up by a total amount

$$\Delta_E - \Delta_L - \Delta_U .$$

Similar reasoning for downward motion indicates that each downward step will be of magnitude

$$(-\Delta_E) - \Delta_L - \Delta_U = -(\Delta_E + \Delta_L + \Delta_U) .$$

Thus one concludes that

1) To make upward motion possible it is necessary that $(\Delta_L + \Delta_U) < \Delta_E$.

2) Downward motion is always possible, even without an extender.

3) The upward and downward rates will be unequal. If the discrepancy must be small it is necessary that the structure be sufficiently rigid so that

$$\frac{\Delta_L + \Delta_U}{\Delta_E} << 1 .$$

ANALYSIS:

(Note: all units are inches, pounds, volts)

The following analysis is an approximate analysis for structural deflection, to develop approximate design criteria. More exact calculations may be made if there are gross discrepancies between this simple theory and experiment.

Consider an actuator of Figure C-1, with parts detailed in Figure C-4. Assume that the "base" and "column" are rigid. The clutch is constructed of n segments of thickness t and of width and height w and h. This clutch works against a cantilever spring of effective length L and cross sectional dimensions B and H.

The clutch is engaged in the de-energized condition (no voltage on clutch piezo-electric material), furthermore let there be an interference δ_i in that condition.

The load to be supported is P pounds.

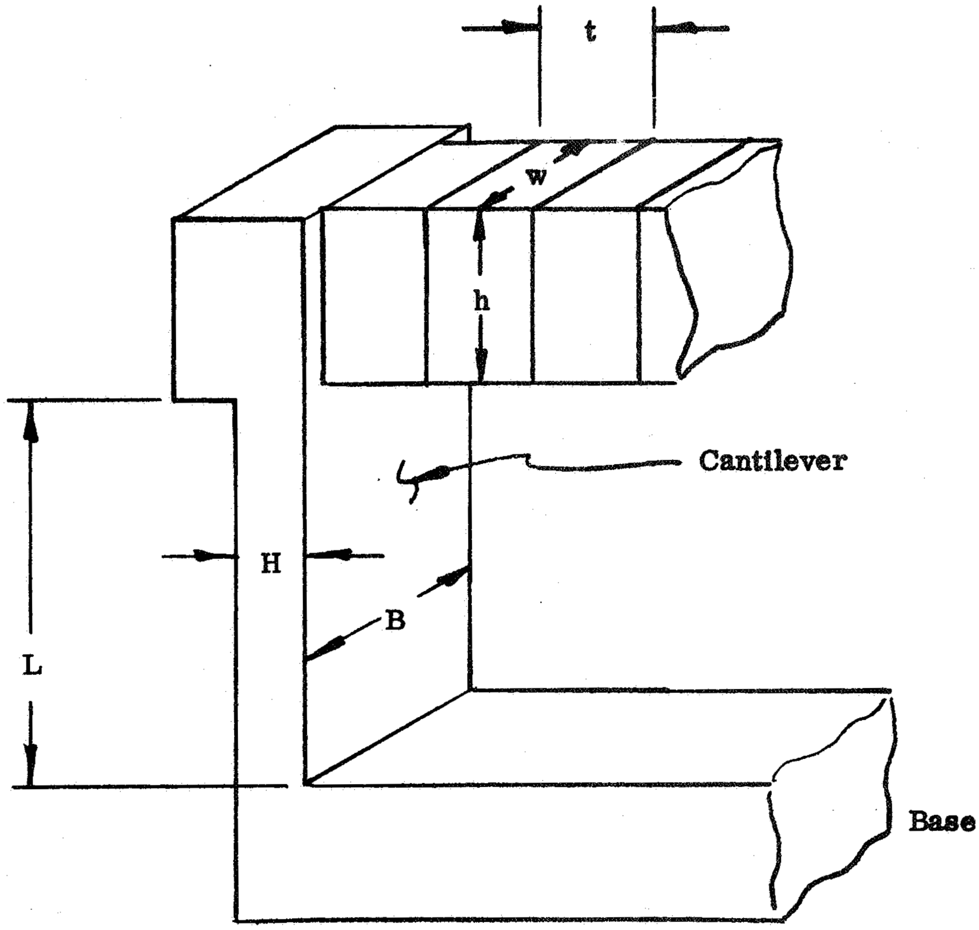


Figure C-4. Clutch Dimensions

1. Calculation of Normal Force

The actuator unit is constructed so as to clutch in the de-energized state. Thus the chips and support cantilever are compressed by an amount δ_i on each side. With a total interference δ_i inches on each side a normal force N is developed on the clutch of magnitude

$$N = (K_1 + K_2)\,\delta_i \tag{C-1}$$

where

$$K_1 = \frac{w\,h}{n\,t\,(S_{33}^D} \quad \text{lb/in.} \tag{C-2}$$

due to compression of the piezoelectric material,

and

$$K_2 = \frac{12\,EJ}{L^3} = BE\,(H/L)^3 \text{ lb/in} \tag{C-3}$$

due to deflection of the cantilever spring.

In these expressions:

n	=	number of layers of piezoelectric material on each side of center.
t, w, h	=	piezoelectric element dimensions (inches)
L, B, H	=	cantilever dimensions (inches)
E	=	cantilever elastic modulus 27×10^6 lbs/in^2
S_{33}^D	=	de-energized compliance of PZT-5H,

$$9 \times 10^{-12} \frac{\text{met}^2}{\text{newton}} = 6.2 \times 10^{-8} \text{ in}^2/\text{lb.}$$

The stress in the piezoelectric material must remain less than the safe limit of 1500 psi

$$\text{Stress} = \frac{K_1\,\delta_i}{wh} = \frac{\delta_i}{n t\, S_{33}^D} < 1500 \text{ psi} \tag{C-4}$$

2. Clutch Clearance, Energized State

The clutch contracts when energized, but the contraction is partly opposed by bending of the cantilever.

The free contraction would be, on each side,

$$\Delta_o = n\,V\,d_{33} \tag{C-5}$$

where

V is the applied voltage, and

d_{33} $= 593 \times 10^{-12}$ met/volt $= 2.34 \times 10^{-8}$ in/volt.

Due to the cantilever restraint this is diminished by an amount Δ_1 given by

$$K_1 \Delta_1 = K_2 (\Delta_o - \Delta_1) \tag{C-6}$$

or

$$\Delta_1 = \left(\frac{K_2}{K_1 + K_2}\right) \Delta_o \tag{C-7}$$

Thus the net deflection is

$$\Delta_o - \Delta_1 = \left(\frac{K_1}{K_1 + K_2}\right) \Delta_o \tag{C-8}$$

and the effective clearance is

$$\Delta_c = \left(\frac{K_1}{K_1 + K_2}\right) \Delta_o - \delta_i \tag{C-9}$$

3. "Lost Motion"

Consider the transfer of load from the lower to the upper clutch (Step 4 in the sequence of Figure C-2). With the load supported by the upper clutch the cantilever support will be in tension and the upper clutch in shear as shown in Figure C-3b. Thus the load is partly supported by each of these members. The total sag is Δ_U.

Thus

$$\frac{1}{2} P = (K_3 + K_4)\,\Delta_U \tag{C-10}$$

where

P is the load supported (nominally, 2.2 lbs)

K_3 is the "spring constant" of the piezoelectric material in shear

and K_4 is the "spring constant" of the cantilever support in tension.

Therefore

$$K_3 = \frac{h\,w\,Y^D_{44}}{nt} \text{ lb/in} \tag{C-11}$$

and

$$K_4 = \left(\frac{BH}{L}\right)E \text{ lb/in} \tag{C-12}$$

Where

$$Y^D_{44} = \frac{1}{S^D_{44}} = \frac{10^{12}}{23.7} \quad \frac{\text{newt}}{\text{met}^2} = 6.12 \times 10^6 \text{ lb/in}^2,$$

the shear modulus of PZT-5H.

Transfer of load from the upper to the lower clutch results in a sag Δ_L equal to Δ_U.

4. Design Considerations

The formulas (C-1) through (C-12) will now be applied to obtain suitable design dimensions. The choice of material (PZT-5H) has already been made. Thus, the design criteria to consider are:

a) There must be sufficient interference δ_i to develop adequate contact pressure and frictional force, but not so much as to exceed the safe compressional loading of the material.

b) When energized there must be adequate clearance, of the order of 40 microinches on each side. Thus the cantilever structure should not be too stiff, since this would curtail the clearance.

c) The total sag ($\Delta_U + \Delta_L = 2\,\Delta_U$) should be small compared with the extender motion. The latter, using 2 chips, could be as large as $2 \times V \times d_{33} = 18.7 \times 10^{-6}$ inches with 400 volt drive. However, much smaller steps, of the order of one microinch are desired. Thus, one would like to maintain the sag at less than 1/3 of the actuator drive and this requires a support structure (K_3, K_4) which is as stiff as possible.

d) There are overall dimensional restrictions of total mechanism width and breadth. Also, to work with standard piezoelectric chips it is convenient to restrict the dimension w to 3/8 inch, and the chip thickness to 1/16 inch. Six chips per side can be accommodated ($n = 6$). Also, the previous considerations (b) and (c) suggest that support rigidity coupled with reasonably low lateral stiffness be achieved by designing the cantilever with dimension B as large as possible, thus B = 0.42 inch is a practical maximum. Dimensions H and L will be chosen to meet the above design criteria.

These considerations lead to design considerations as follows:

a) The maximum compression load (1500 psi) restricts the interference to:

$\delta_i < (1500)\ nt\ S_{33}^D$ (From equation C-4)

$\delta_i < 35 \times 10^{-6}$ in.

Thus nominal interference of the order of 15 microinch will be perfectly safe.

b) With 400 volt drive (a safe value) the free contraction(equation C-5) will be 56 microinches. This will be diminished by Δ_1 due to the spring load (equation C-7). Thus, from C-6 or C-7 we may obtain relations between Δ_1 and K_2/K_1:

$$\frac{K_2}{K_1} = \frac{\Delta_1}{\Delta_o - \Delta_1} \tag{C-13}$$

Δ_1(microinches	0.5	1	2	4
(K_2/K_1)	0.009	0.0182	0.037	0.077

From C-2 and C-3

$$\frac{K_2}{K_1} = (H/L)^3 \quad \frac{BE(S_{33}^D)\, n t}{w\, h} \tag{C-14}$$

With dimensions;

$w = 0.375$

$t = 0.0625$

$n = 6$

$B = 0.420$

This becomes

$$\frac{K_2}{K_1} = \left(\frac{0.703}{h}\right)\left(\frac{H}{L}\right)^3$$

Thus, from C-13 and C-14 we obtain relations between

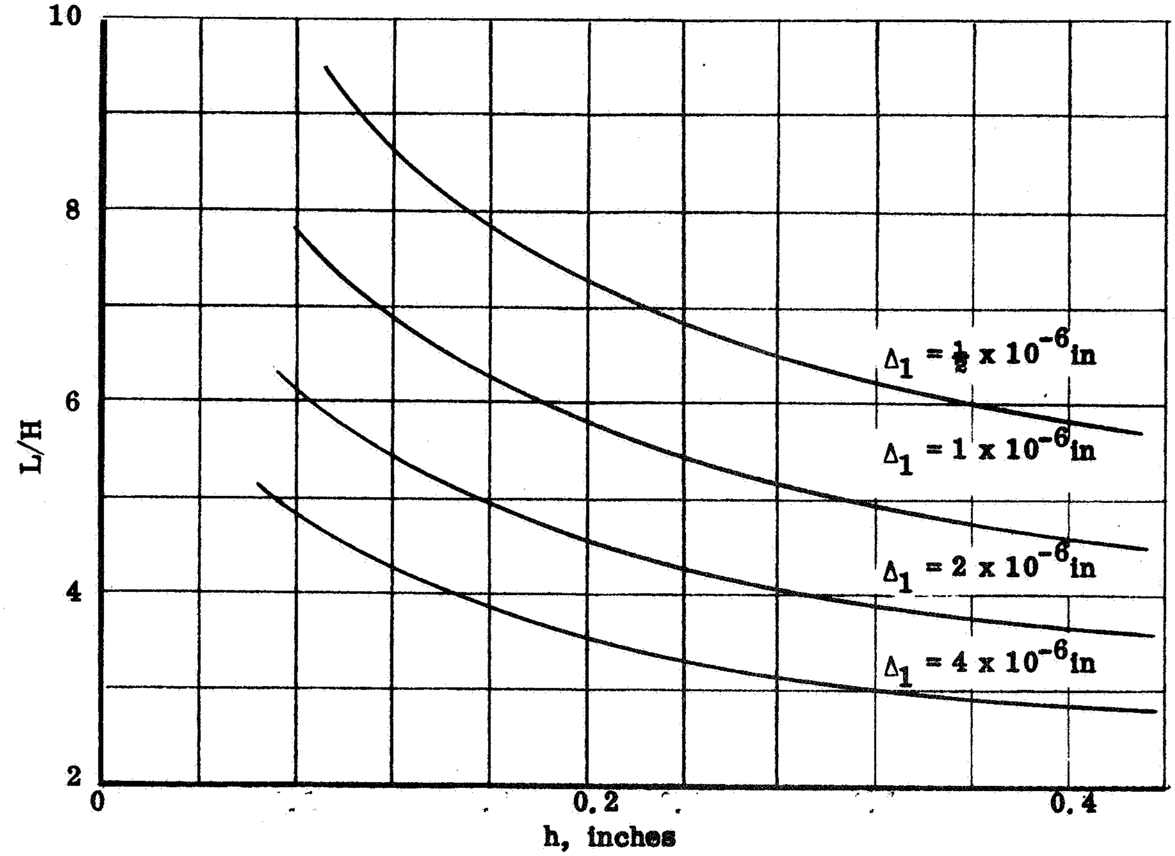
chip dimension h
beam stiffness H/L
Spring ratio K_2/K_1
Deflection Δ_1

This is illustrated in the upper set of curves of Figure C-5.

Equations C-11 and C-12 may now be evaluated, using these dimensions, as shown in the lower set of curves, Figure C-5. Finally, using these numbers for K_3 and K_4 in equation C-10 we may solve for the total sag $\Delta_U + \Delta_L = 2\Delta_U$ as shown in Figure C-6.

5. Design Selection

Figure C-5 indicates that practical values of "lost motion" of the order of 0.3 to 0.6 microinches are achievable, but probably no smaller. (The family of curves shown could be extended somewhat, theoretically. However for very stiff structures, the basic assumption of very stiff base and column, Figure C-1, would no longer be tenable.) The design has therefore been implemented according to the drawing, Figure 11 of the main report, with $h = 0.3$ in. The cantilever


10
8
6
4
2
L/H
0
0.2
0.4
h, inches
$\Delta_1 = \frac{1}{2} \times 10^{-6}$in
$\Delta_1 = 1 \times 10^{-6}$in
$\Delta_1 = 2 \times 10^{-6}$in
$\Delta_1 = 4 \times 10^{-6}$in

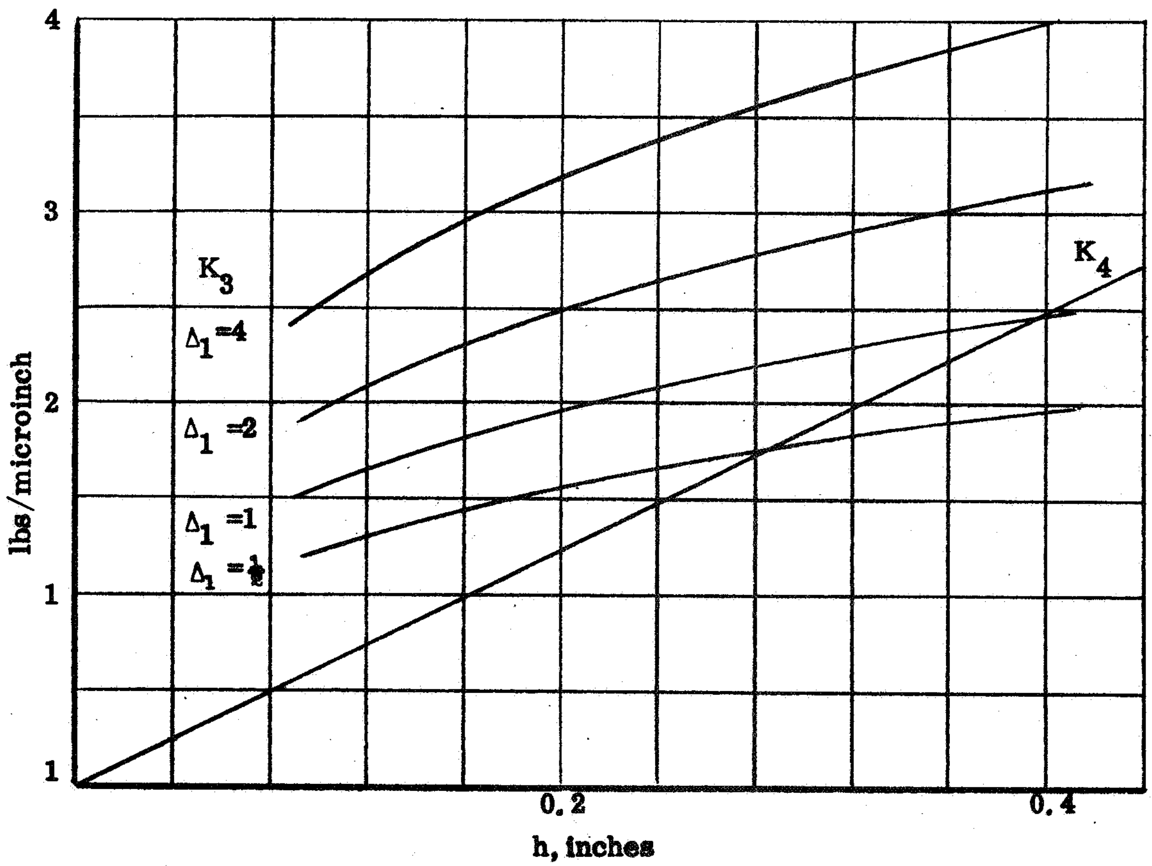
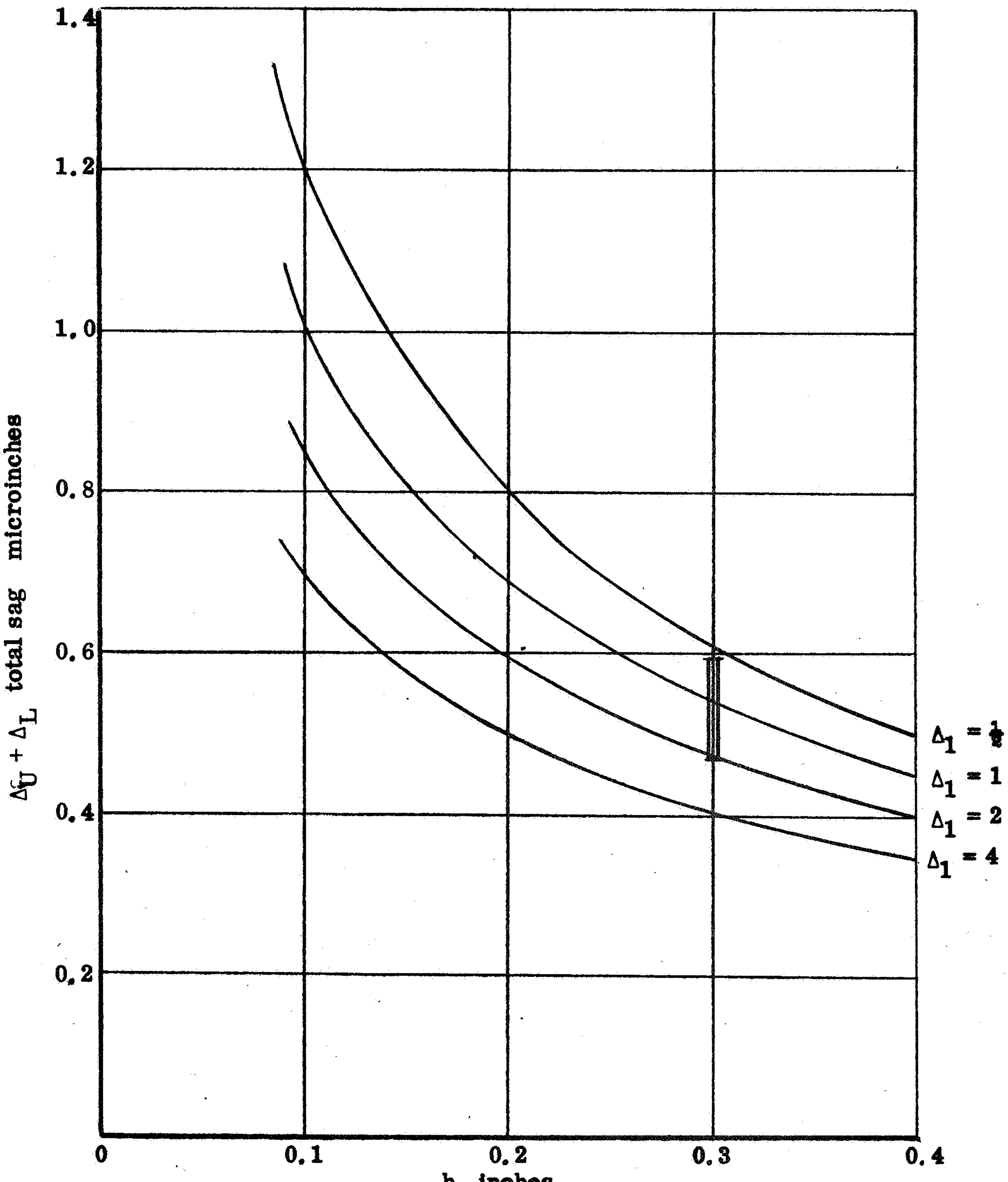

4
3
2
1
1
lbs/microinch
K_3
$\Delta_1 = 4$
$\Delta_1 = 2$
$\Delta_1 = 1$
$\Delta_1 = \frac{1}{2}$
K_4
0.2
0.4
h, inches

Figure C-5



1.4
1.2
1.0
0.8
0.6
0.4
0.2
$\Delta_U + \Delta_L$ total sag microinches
$\Delta_1 = \frac{1}{2}$
$\Delta_1 = 1$
$\Delta_1 = 2$
$\Delta_1 = 4$
0
0.1
0.2
0.3
0.4
h, inches

Figure C-6

is a rather complex structure, the dimensions shown in Figure 12 of the main report indicate a ratio of

$$4 < \frac{L}{H} < 6$$

$$0.0366 > K_2/K_1 > 0.0108 \text{ lbs}/\mu \text{ inch}$$

$$2 > \Delta_1 > 0.6 \ \mu \text{ inch}$$

$$0.47 < 2\Delta_U < 0.59 \ \mu \text{ inch.}$$

With this lost motion of $\frac{1}{2}$ μinch it is suggested that the extender drive be made approximately 2 μ inch per step, resulting in operation of

Upward (against the load) motion: 1.5 μinch/cycle
Downward(with the load) motion: 2.5 μinch/cycle.