TECHNICAL REPORT

NASA CR-158974

Final Report No. F-C4705

DESIGN AND TEST OF THE 172K FLUIDIC RUDDER

by

Charles A. Belsterling

Prepared under Contract No. NAS1-14893

by

The Franklin Research Center
Philadelphia, Pennsylvania 19103

October 1978

for

NASA
National Aeronautics and
Space Administration
Langley Research Center
Hampton, VA 23665

Franklin Research Center
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1. Report No.
NASA CR-158974

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Design and Test of the 172K Fluidic Rudder

5. Report Date
October 1978

6. Performing Organization Code

7. Author(s)

Charles A. Belsterling

8. Performing Organization Report No.
F-C4705

9. Performing Organization Name and Address

Franklin Research Center
Philadelphia, PA 19103

10. Work Unit No.

11. Contract or Grant No.
NAS1-14893

12. Sponsoring Agency Name and Address
Langley Research Center
National Aeronautics & Space Administration
Hampton, VA 23665

13. Type of Report and Period Covered
Final Report 4/77 - 10/78

14. Sponsoring Agency Code

15. Supplementary Notes
Final Report
NASA Project Manager, H. Douglas Garner, Flight Instrument Division

16. Abstract

This report describes further progress in the development of concepts for control of aircraft without moving parts or a separate source of power. Previous phases of the work covered wind tunnel tests of various scale models of a Fluidic Rudder, intended to become the force-producing element in a closed loop automatic stabilization system. This report documents the design and wind tunnel tests of a full-scale Fluidic Rudder for a Cessna 172K aircraft, intended for subsequent flight tests.

The 172K Fluidic Rudder was designed to provide a control force equivalent to 3.3 degrees of deflection of the conventional rudder. In spite of an extremely thin airfoil, cascaded fluidic amplifiers were built to fit, with the capacity for generating the required level of control force. Wind tunnel tests once again demonstrated that the principles of lift control using ram air power are sound and reliable under all flight conditions. The tests also demonstrated that the performance of the 172K Fluidic Rudder is not acceptable for flight tests until the design of the scoop is modified to prevent interference with the lift-control phenomenon.

17. Key Words (Suggested by Author(s))
Flight Control
Aircraft Stabilization
Fluidics
Aerodynamics

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
42

22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

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By Charles A. Belsterling
The Franklin Research Center

INTRODUCTION

This report describes further progress in the successful development of concepts for control of aircraft without moving parts or a separate source of power. Previous phases of the work covered the wind tunnel tests of various scaled models of a Fluidic Rudder, intended to become the force-producing element in a closed-loop automatic stabilization system. In this report we document the design and test of a full-scale Fluidic Rudder for a Cessna 172K aircraft, intended for subsequent flight tests. The results indicate that a practical Fluidic Rudder can be constructed with fluidic amplifiers with the potential for controlling an aerodynamic force equivalent to more than 0.05 radians (3 degrees) of total conventional rudder deflection.

CALCULATION OF REQUIRED SLOT AREA

In early discussions with NASA technical personnel, it was agreed that a realistic performance goal for the 172K Fluidic Rudder was to develop an aerodynamic force equivalent to 3 degrees deflection of the conventional rudder. This force should be enough to implement an effective wings-leveling system on a Cessna 172K aircraft. To this date we have not had the opportunity to develop the aerodynamic theory necessary to calculate the required slot size from basic principles. Therefore empirical methods based on test results of six previous scoop-fed slotted airfoils were applied.* The significant factor in developing aerodynamic force is the ratio of slot area to total airfoil area. To develop a force equivalent to 0.055 radians (3.3 degrees) of rudder, this factor must be 0.024.

A plan view of the complete vertical tail assembly on the Cessna 172K aircraft is shown in Figure 1. The total area is 14787 cm^2 (2292 in^2) and the slots can be located just forward of the conventional rudder, running full span except for breaks due to rib interference. Using the ratio of slot area to airfoil area of 0.024, the required slot area is:

$$\text{slot area} = 0.024 \times 14787\ cm^2 = 354\ cm^2\ (54.9\ in^2)$$

*"Design and Laboratory Test of the 172K Fluidic Rudder", FRC Summary Report No. C4705-1.

SLOT FLOW AMPLIFIER DESIGN

The span available for open slots is (see Figure 1) approximately 127 cm (50 in.), so the average slot width must be 2.79 cm (1.1 in.).

The Cessna 172K Vertical Tail combines a very significant taper in chord length with a reduction in airfoil dimensions from an NACA 0009 at the root to an NACA 0006 configuraiton at the tip. The result is an extremely thin airfoil whose dimensions just forward of the rudder hinge span, where the slots must be located, are relatively small. Therefore it became necessary to construct the slot flow amplifiers in 4 sections with continuously-tapering dimension from root to tip.

To stabilize the critical dimensions of the slot flow amplifiers throughout the length of their span, they were designed to have 24 gaging ribs illustrated in Figure 2 spaced approximately 5.1 cm (2.0 in.) apart. The calculated dimensions for these ribs are given in Table 1.

Figure 3 shows a typical slot flow amplifier in various stages of construction. The ribs and end plates are made from 0.16 cm (1/16 in.) aluminum stock and the spanwise sections are shaped from hard maple wood. There are a total of four such units.

DRIVER AMPLIFIER DESIGN

As in the case of the slot flow amplifier, the driver amplifier had to be redesigned to fit into the limited space inside the 172K airfoil. The major change was in the distance from the power nozzle to the output ports, requiring a change in the angle of the receiver walls. The non-dimensional configuration is shown in Figure 4. Four of these amplifiers are required to drive the four sections of slot flow amplifiers. Each one has a different capacity. However, we minimized the number of designs by choosing only two cross-sections and building them with two aspect ratios each. They were designed for a flow gain of 4, so the power nozzle area is 1/4 of the area of the slot flow amplifier control nozzle it drives. Dimensions are given in Table 2. A typical model is shown in Figure 5.

The driver amplifiers are constructed of Plexiglas and are fitted with valving mechanisms to alternately close one input port or the other. The mechanism is operated by a miniature air cylinder which can be remotely controlled through 0.16 cm (1/16 in.) ID tubing.

CASCADED AMPLIFIER SETS

The appropriate driver amplifiers are connected to their slot flow amplifiers through aluminum ducts. These ducts deliver the total flow from the driver output ports to the slot flow amplifier control ports. They are designed for a modest expansion ratio of approximately 3.5.

Table 1. Slot Flow Amplifier Dimensions

CENTIMETERS (See Figure 2)

	N	AIRFOIL THICKNESS T	SLOT HEIGHT H	POWER NOZZLE WIDTH A	RECEIVER RADIUS R	TOTAL EXIT WIDTH HX	EXIT DISTANCE DX	SPLITTER DISTANCE D	CONTROL NOZZLE WIDTH B	SLOT WIDTH W	SLOT AREA SA
AMP. #1	1	4.24	.0	.84	1.19	2.24	4.47	1.68	.21	1.89	.00
	2	4.44	5.1	.88	1.24	2.35	4.69	1.76	.22	1.98	9.82
	3	4.61	5.1	.91	1.29	2.43	4.86	1.82	.23	2.05	10.24
	4	4.75	5.1	.94	1.33	2.51	5.01	1.88	.23	2.11	10.58
	5	4.95	5.1	.98	1.39	2.61	5.22	1.96	.25	2.21	10.97
	6	5.12	5.1	1.01	1.44	2.70	5.40	2.02	.25	2.28	11.39
AMP #2	7	5.12	.0	1.01	1.44	2.70	5.40	2.02	.25	2.28	.00
	8	5.33	6.3	1.06	1.50	2.81	5.63	2.12	.26	2.37	14.77
	9	5.50	5.1	1.09	1.54	2.90	5.80	2.18	.27	2.45	12.25
	10	5.65	5.1	1.12	1.59	2.98	5.96	2.24	.28	2.52	12.61
	11	5.82	5.1	1.15	1.64	3.07	6.13	2.30	.29	2.59	12.97
	12	6.03	6.3	1.19	1.70	3.18	6.36	2.38	.30	2.69	16.75
AMP #3	13	6.10	.0	1.21	1.71	3.22	6.43	2.42	.30	2.71	.00
	14	6.26	5.1	1.24	1.76	3.30	6.60	2.48	.31	2.79	13.97
	15	6.52	7.6	1.29	1.83	3.44	6.87	2.58	.32	2.90	21.67
	16	6.77	7.6	1.34	1.91	3.57	7.14	2.68	.33	3.01	22.53
	17	7.02	7.6	1.39	1.98	3.71	7.41	2.78	.35	3.13	23.39
	18	7.28	7.6	1.44	2.05	3.84	7.67	2.88	.36	3.24	24.26
AMP #4	19	7.37	.0	1.46	2.08	3.89	7.77	2.92	.36	3.28	.00
	20	7.52	5.1	1.49	2.12	3.97	7.93	2.98	.37	3.35	16.84
	21	7.78	7.6	1.54	2.19	4.10	8.20	3.08	.38	3.46	25.95
	22	8.03	7.6	1.59	2.27	4.24	8.47	3.18	.40	3.58	26.81
	23	8.29	7.6	1.64	2.34	4.37	8.74	3.28	.41	3.69	27.68
	24	8.54	7.6	1.69	2.41	4.51	9.01	3.38	.42	3.80	28.54

TOTAL AREA=354.00
PERCENT=93.%

Table 2. Driver Amplifier Design Dimensions

	Dimensions in Centimeters			
	Amp No. 1	Amp No. 2	Amp No. 3	Amp No. 4
Power Nozzle A	.930	.930	1.60	1.60
Control Nozzle B	.232	.232	.399	.399
Splitter Distance C	1.39	1.39	2.39	2.39
Receiver Width D	1.37	1.37	2.34	2.34
Radius R	4.17	4.17	6.35	6.35
Length X	9.04	9.04	10.9	10.9
Height Y	5.26	5.26	6.35	6.35
Span Z	6.35	8.28	7.62	8.89
Wall Angle α	21°	21°	21°	21°

Figure 6 shows the cascaded set of amplifiers for position No. 3 (see location in Figure 7). This set was chosen for instrumentation so there are twin differential pressure taps into the driver control chambers and the slot flow control chambers. Note that each set is a rigid package mounted at the trailing end.

Figure 7 shows the layout of the 4 sets of cascaded amplifiers in the airfoil.

SCOOP DESIGN

The ratio of scoop area to slot area necessary to recover about 80% in the plenum chamber has been determined empirically as 1.8. The slot area is 354 cm^2 (54.9 $in.^2$) so the frontal area of the scoop should be 645 cm^2 (100 $in.^2$). In discussions with Cessna personnel, it was decided that the speed fairing at the base of the vertical fin on the 172K aircraft should remain in place. This means that the fairing would project into the scoop, reducing the effective frontal area. Therefore the scoop was made 1020 cm^2 (158 $in.^2$) to compensate for the fairing.

The remainder of the scoop design is the result of a number of compromises including readily-available materials, the limited area for entering the airfoil and the cost of construction. External aerodynamics was considered a secondary factor. The resulting scoop design is shown in Figure 8.

FLUIDIC RUDDER ASSEMBLY

In addition to the fluidic amplifiers and the scoop, the 172K Fluidic Rudder also includes 3 different pressure transducers for measuring the dynamic characteristics of the amplifiers remotely. Tubing is also brought out of the base of the model for the 4 differential pressure taps in the amplifiers and for two static ports in the plenum located on the two midspan ribs.

In addition to the air cylinders to control the "step" inputs to the driver amplifiers from a remote location, we have also provided a cord and pulley system to enable the incremental control of signals for plotting static characteristics.

Figure 9 shows the various stages in the assembly of the 172K Fluidic Rudder before the skin was riveted in place.

LABORATORY TESTS OF THE 172K FLUIDIC RUDDER

Following the final assembly of the Fluidic Rudder vertical fin, it was set up for laboratory tests as shown in Figure 10. The large blower is capable of delivering a measured pressure in the plenum chamber of 3.8 cm h_2o (1.5 in h_2o).

Using the manual cord controls and the differential pressure transducers, we plotted continuous curves of the static characteristics of the fluidic amplifiers of set No. 3. All plots are made with equal sensitivities in the input and output channels so the slope of the curves is the actual pressure gain.

The characteristics of the No. 3 slot flow amplifier are shown in Figure 11. Note that it has a high gain, is quite symmetrical and very nearly cuts off all flow out the unwanted slot.

Figure 12 shows the characteristic of the No. 3 driver amplifier. It has a gain of nearly 1.5 and shows some evidence of approaching saturation.

Figure 13 shows the characteristics of the cascaded No. 3 driver and slot flow amplifiers. It shows that they are exceptionally well-matched and provide a wide range of control of the air flow from the slots.

Dynamic tests were run in the Laboratory by switching pressure applied to the miniature air cylinder controlling the inlets to the No. 3 driver amplifier. The signals from the three internal pressure transducers were recorded simultaneously on a strip-chart recorder with equal sensitivity in all channels. Test results are illustrated in Figure 14. Note that the input signal is not a perfect step but has a rise time (10-90%) of less than 35 milliseconds (msec). The driver amplifier then responds in less than 25 msec. and the slot flow amplifier 25 msec. later. The overall response time of the cascaded set No. 3 is less than 75 msec.

WIND TUNNEL TESTS

The second Phase of the project was dedicated to the wind tunnel testing of the full-scale Fluidic Rudder designed for the Cessna 172K aircraft. The objective of these tests was to establish the static control and dynamic response characteristics of the Rudder before it was installed on the aircraft for flight testing. Tests were conducted in the 3.66 m (12 ft.) tunnel in Building 646 at Langley Research Center, NASA, during the week of June 19, 1978.

Model Description

The wind tunnel test model shown in Figure 15 is a full-scale vertical stabilizer and rudder assembly for a Cessna 172K aircraft. It has been modified with a 0.36 m (14 in.) ID scoop at the base of the stabilizer straddling the existing fairing. The airfoil is sealed to act as a plenum for the recovery of ram air collected by the scoop. Inside the airfoil is a set of fluidic amplifiers configured to control the exit flow of the recovered air from slots in both airfoil surfaces running full-span at about 55% chord. Changing the proportions of flow from these slots alters the net circulation around the airfoil to create a differential "lift" force that acts like the movable rudder to generate yaw moments on the aircraft for control. Details of the design are given in FRC Summary Report No. C4705-1, "Design and Laboratory Test of a Fluidic Rudder for the Cessna 172K."

The purpose of the planned series of wind tunnel tests was threefold, as follows:

1. In static tests, establish the proportional control characteristics of the fluidic rudder
2. In static tests, calibrate the effect of the scoop-fed slots against the movable rudder
3. In dynamic tests, record the model lift and drag response to step changes in signals to the fluidic amplifiers.

To implement these tests, the model has been fitted with a set of static and total pressure probes to measure:

1. plenum pressure inside airfoil (2)
2. control differential pressure to drive amplifier #3
3. control differential pressure to slot flow amplifier #3
4. total output differential pressure of airstream exiting from slots.

These quantities were displayed side-by-side with tunnel pitot-static pressures on a multi-tube manometer bank.

The model has also been fitted internally with three differential pressure transducers to detect:

1. control differential pressure to driver amplifier #3
2. control differential pressure to slot flow amplifier #3
3. total output differential pressure of air-stream exiting from slots #3.

These quantities were recorded on a multi-channel strip chart recorder simultaneously with lift or drag.

The model has been provided with the means to introduce small incremental changes in control signals through a push-pull cable operated from the control room. It also has miniature, remotely-controlled air cylinders on valving mechanisms to introduce step changes in control signals for dynamic response tests.

Forces and moments generated in the model in the wind tunnel were measured through the six-degree-of-freedom balance and instrumentation with which it is normally equipped. Automatic computation was set up to calculate lift and drag in pounds and pitching moment in pound feet.

Test A - Baseline Characteristics

An initial set of runs was made to check out the instrumentation and to measure the baseline characteristics of the 172K Fluidic Rudder. Angle of attack and rudder deflection were set at zero. In the first run, all slots were taped over to provide the cleanest possible airfoil, but the scoop was opened. In the second run, the tape was removed from all slots on the left side forcing all system air flow to exit from them. In the third run, all slots on the right side were open while all slots on the left side were again closed with tape. The test results were as follows:

	LIFT (+ Left)	DRAG (+ Aft)
All slots closed	-34.5 N (-7.753 lb.)	58.3 N (13.1012 lb.)
Left slots open	-35.0 N (-7.871 lb.)	58.7 N (13.1897 lb.)
Right slots open	-29.3 N (-6.579 lb.)	61.4 N (13.8094 lb.)
Effect of left slots	-0.52 N (-0.118 lb.)	0.39 N (+0.0885 lb.)
Effect of right slots	+5.22 N (+1.174 lb.)	3.55 N (+0.7974 lb.)
Max. differential	5.75 N (1.292 lb.)	3.15 N (0.7089 lb.)

Figure 16 shows the characteristics of the airfoil with zero rudder deflection δ_R; lift and drag versus angle of attack. The double points bracket the readings between maximum differential slot flows.

Figure 17 shows the characteristics of the airfoil at zero angle of attack α; lift and drag versus rudder deflection. Again the double points bracket the readings between maximum differential slot flows. Note the decreasing drag with rudder angles to the left.

Static tests were also run at a later date on a standard Cessna 172K Vertical Tail Assembly for direct comparison with the 172K Fluidic Rudder. The results are as follows for zero angles of attack and rudder deflection:

	Lift	Drag
Standard 172K Assembly	34.1 N (-7.675 lb.)	23.4 N (5.2523 lb.)

Test B - Static Characteristics with Zero Rudder and Angle of Attack

This set of measurements was made with all slots open, starting with maximum flow from the right slots. The signal to the driver amplifiers was varied by small increments by means of the push-pull control cable and all variables were recorded at each increment. The test results are shown in Figure 18 through Figure 22.

Figure 18 shows the characteristic of the cascaded fluidic amplifiers in set #3. It indicates that they are performing well as expected from laboratory tests. Figure 19 is the characteristic of the slot flow amplifier alone showing the exceptional balance and gain resulting from the new dimensionally-controlled design. Figure 20 is the characteristic of the driver amplifier alone, indicating the anticipated linearized gain but with some unbalance at null.

Figure 21 shows the lift and drag characteristics of the Fluidic Rudder alone ($\alpha=0$, $\delta_R=0$). They indicate a definite trend, but the spread of the data points prevents precise definition of either curve.

Test C - Static Characteristics as a Function of Rudder Deflection

The static characteristics of the airfoil alone were recorded at zero angle of attack for rudder deflection from -0.087 rad (-5°) (rudder right) to +0.101 rad. (+6°). The results demonstrate similar variations in lift and drag due to slot flows throughout this range of angles. Figure 22 shows the characteristics for a rudder angle of -0.087 rad. (-5°). Figure 23 is for a rudder angle of +0.087 rad. (+5°). Some difference in effectiveness may be indicated.

Test D - Static Characteristics as a Function of Angle of Attack

The static characteristics of the airfoil alone were recorded with zero rudder angle for angles of attack from -0.070 rad. (-4°) (nose left) to +0.021 rad. (+12°). The results demonstrate similar variations in lift and drag due to slot flows throughout this range of angles. Figure 24 shows typical characteristics of an extreme combination of angles of attack and rudder deflection.

Test E - Dynamic Response of the 172K Fluidic Rudder System

Dynamic response tests of the 172K Fluidic Rudder were run covering all combinations of angles-of-attack-and-rudder deflection tested statically. Results were similar in every case. Figure 25 shows a typical response of lift for angles of attack and rudder deflection both zero. These traces display the relative magnitudes of signal and "noise" in measuring lift confirming the reason for point scatter in static measurements. Although it is difficult to estimate precise values, the study of a large number of repeated tests leads to an estimated response curve indicated by the dashed trace in Figure 25. The rise time of the fluidic amplifiers is less than 50 milliseconds and the overall response of the 172K Fluidic Rudder is less than 200 milliseconds.

Repeated tests of drag response failed to show any measurable amount of change.

CALCULATION OF EQUIVALENT RUDDER DEFLECTION

To determine the equivalent effectiveness of slot flow control compared with conventional rudder deflection, we refer first to Figure 17. This curve has a slope of approximately 714 N/rad (2.80 lb/degree). Then with reference to Figure 21, we estimate an average maximum incremental change in lift due to slot flows of approximately 7.12 N (1.60 lbs.). Therefore the effectiveness of slot flow control in the present 172K Fluidic Rudder is 7.12 N/714 N per rad = 0.01 rad (0.57 deg.). Compared with the results of previous tests of six different slot flow control models, this is only about 20% of the amount anticipated.*

FURTHER STUDIES OF THE 172K FLUIDIC RUDDER

Recognizing that the present design is not representative of the true potential of the Fluidic Rudder, further studies were made of the wind tunnel data. Figures 18, 19 and 20 prove that the fluidic amplifiers have the gain characteristics they were designed for and demonstrated in laboratory tests.

However, Figures 21 through 25 show that the airfoil's response to changes in slot flows is relatively weak. Therefore we initiated tuft studies of the aerodynamics of the airfoil in the wind tunnel. Figure 26 shows the flow patterns over one surface for angles of attack, zero and +0.14 rad. (+8°) (nose left). The pattern clearly shows a massive vortex behind the scoop which sweeps over most of the lower half of the airfoil. The situation is aggravated at higher angles of attack. Since our largest and potentially most effective slots are desigend to act on the lift generated in this area, this accounts for a major portion of the deviation from expected performance. Therefore the external aerodynamics of the scoop are clearly not acceptable.

Table 3 is a set of readings from the manometer bank. The calculations show that the slot flow amplifiers are 100% efficient in handling

*FRC Summary Report No. C4705-1, August 1978

Table 3. Significant Readings from Manometer Bank

Angle of Attack α	Tunnel Dynamic Pressure $P_t - P_s$	Plenum Recovered Pressure $P - P_s$	Slot Dynamic Differential ΔP_3	% Recovery in Plenum $\frac{P - P_s}{P_t - P_s}$	Slot Flow Amplifier Efficiency $\frac{\Delta P_3}{P - P_s}$	Overall % Recovery $\frac{\Delta P_3}{P_t - P_s}$
0	1.10	0.45	0.45	41	100	41
+ 8°	1.10	0.40	0.40	36	100	36

the energy recovered in the plenum. This figure is difficult to accept until one realizes that they exit into a region of the airfoil where the pressure is below the tunnel static pressure.

The calculations also show that only 41% of the tunnel dynamic pressure is recovered in the plenum. Previous models have demonstrated nearly 80% recovery (see CR-132568) using similar dimensional ratios. This deficiency accounts for a second major loss in effectiveness of the 172K Fluidic Rudder. Therefore the internal aerodynamics of the scoop and ducts leading into the plenum are clearly not acceptable.

SUMMARY AND CONCLUSIONS

Based on the designs of six previously-tested scoop-fed slotted airfoils, the Fluidic Rudder for the Cessna 172K aircraft has been successfully built and tested in the Laboratory. It has the potential for providing a control force equivalent to 0.55 radians (3.3 degrees) of total deflection of the conventional rudder.

The wind tunnel tests described in this report have once again demonstrated that the principles of lift control using ram air power are sound and reliable under all reasonable flight conditions. They have proved that stable and repeatable fluidic amplifiers can be designed and built into an airfoil to yield predictable results. They have also confirmed that slot flow control is compatible with normal control using conventional moving surfaces.

These tests have also demonstrated that the performance of the present 172K Fluidic Rudder is not acceptable for flight testing. Analyzing the results leads clearly to the conclusion that the existing scoop and inlet passages should be modified to eliminate

1. separation of flow behind the inlet
2. interference with the effect of the slot flow
3. excessive duct losses
4. excessive drag.

These modifications are expected to lead to the realization of the design goal for the 172K Fluidic Rudder of an equivalent effectiveness of better than 3 degrees of total conventional rudder.

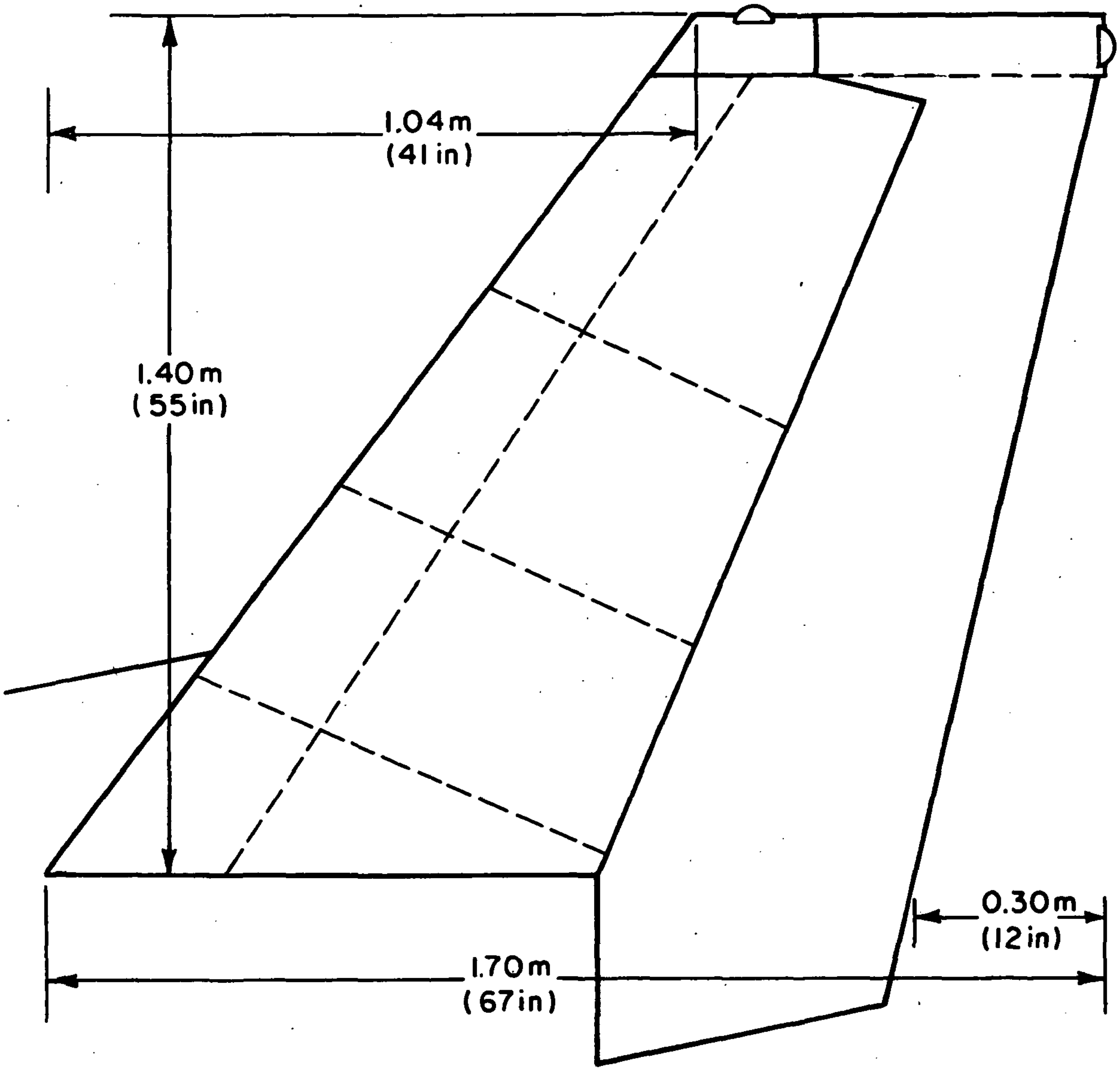
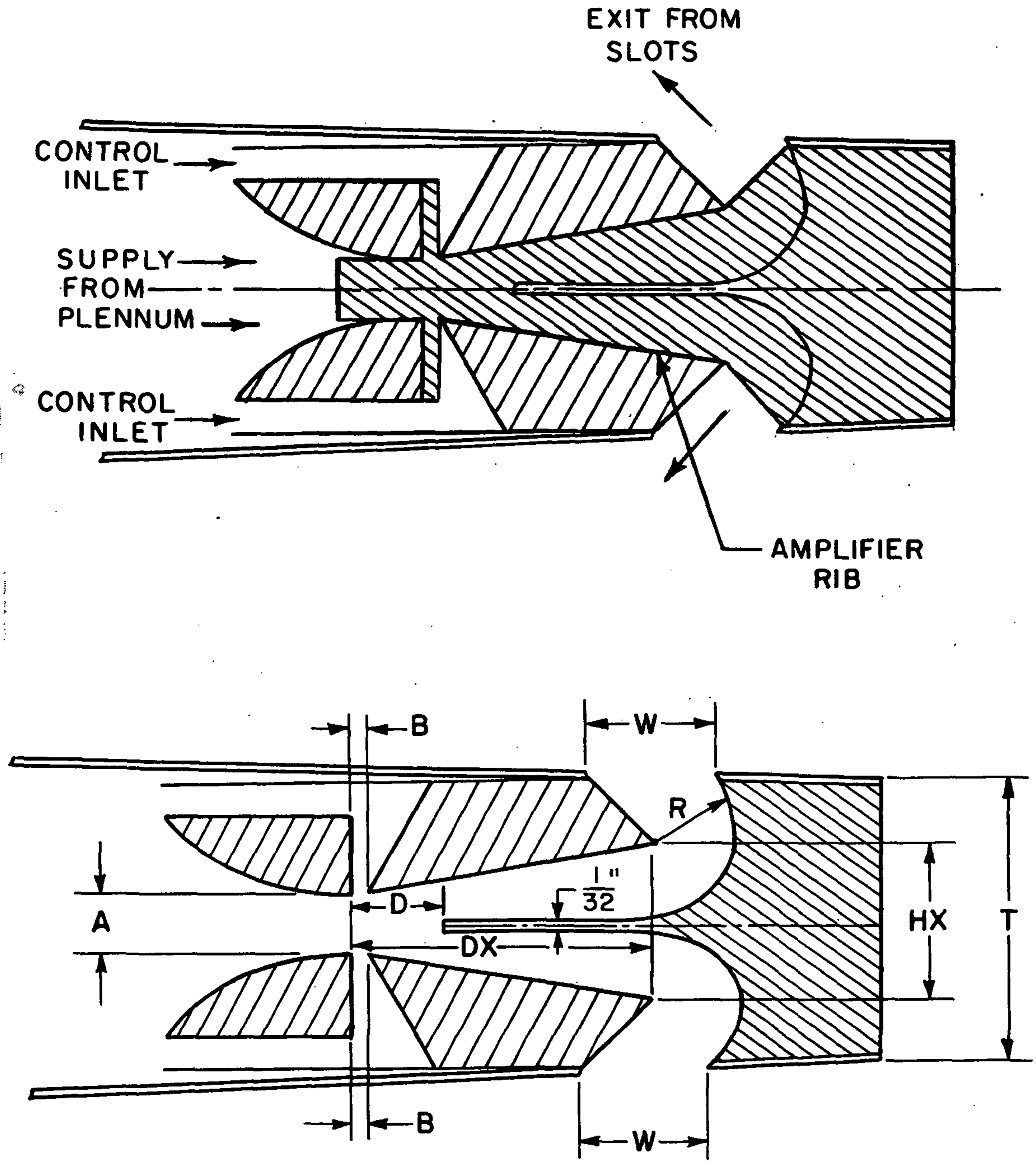


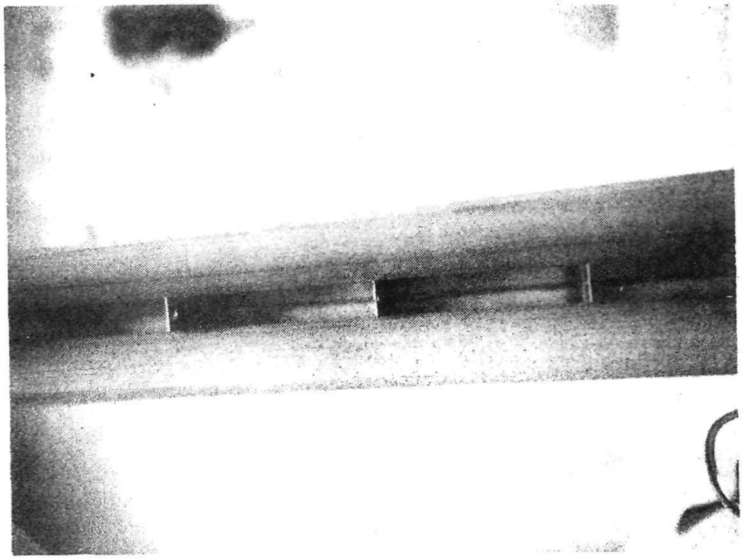
Figure 1. Dimensions of the Cessna 172 K Vertical Tail Assembly



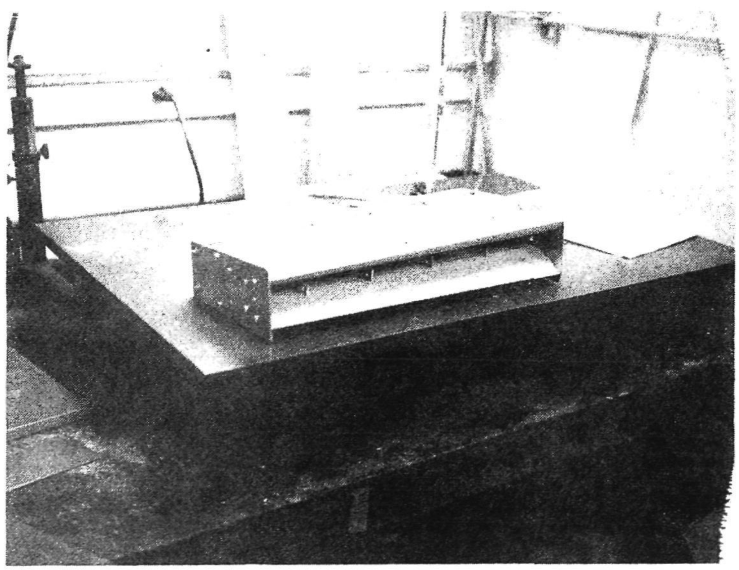
H = DISTANCE BETWEEN RIBS

SA = SLOT AREA BETWEEN RIBS
(SEE TABLE 1)

Figure 2. Slot Flow Amplifier



Assembly Looking into Power Nozzle



Complete Assembly

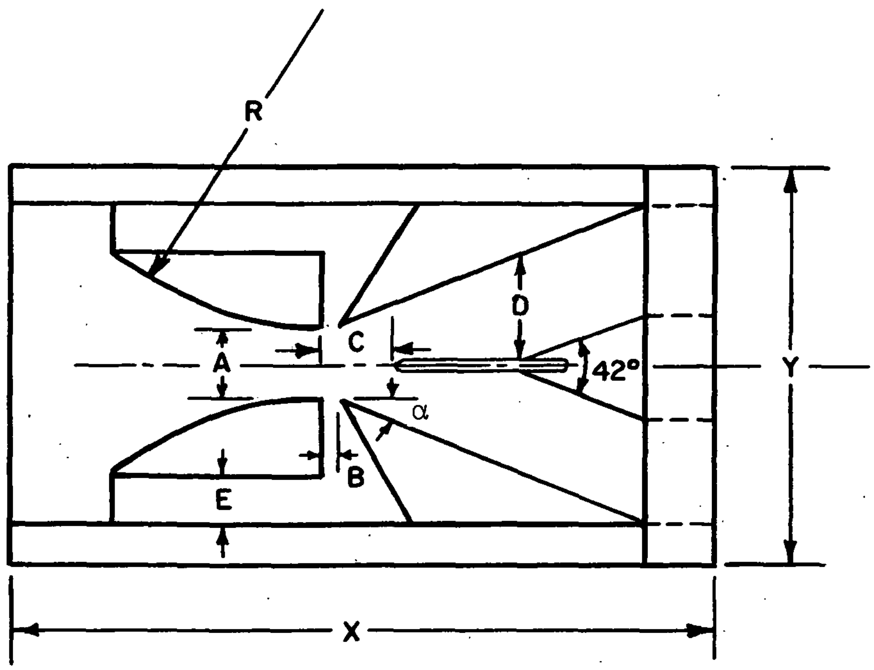


Figure 4. Non-Dimensional Cross-Section of Driver Amplifiers

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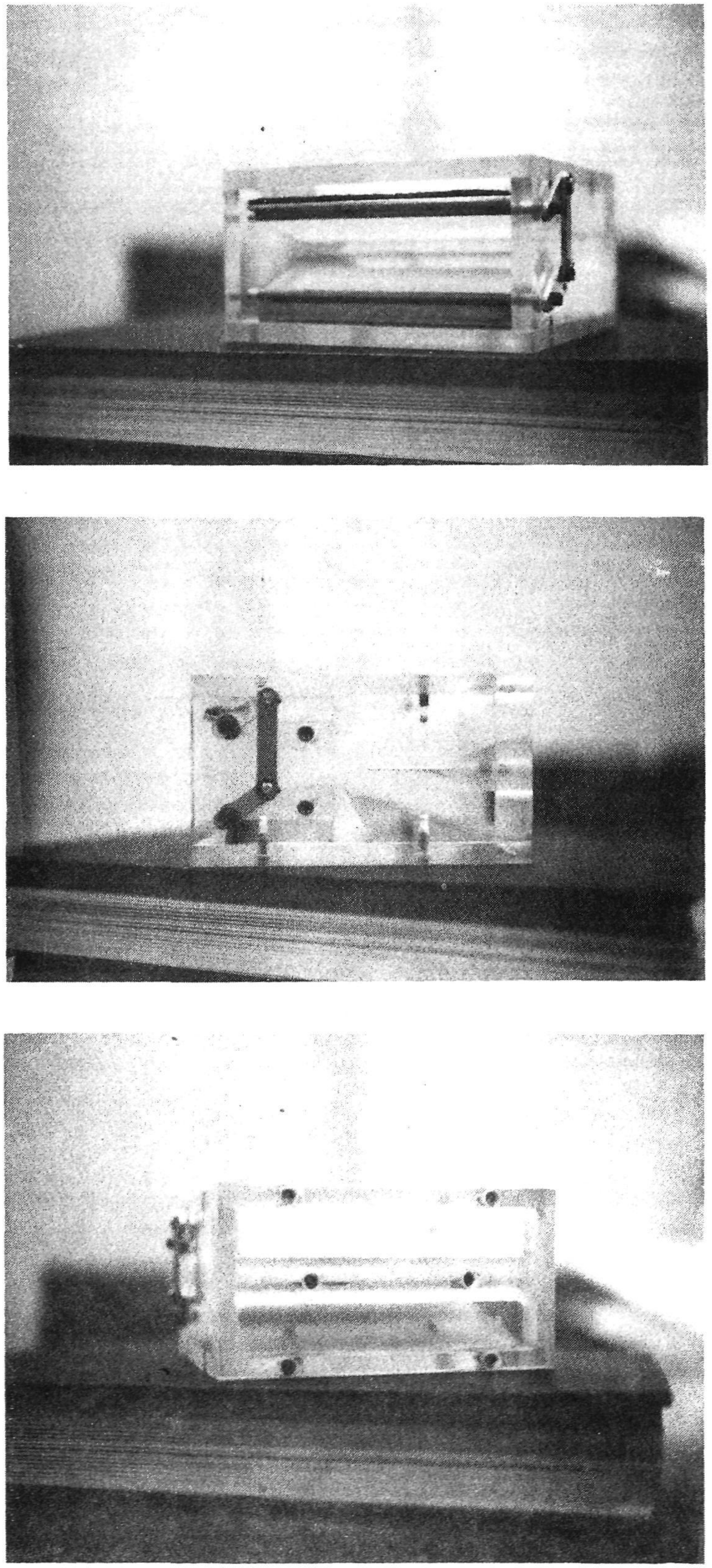

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Figure 7. Typical Driver Amplifier with Remote Control Mechanism

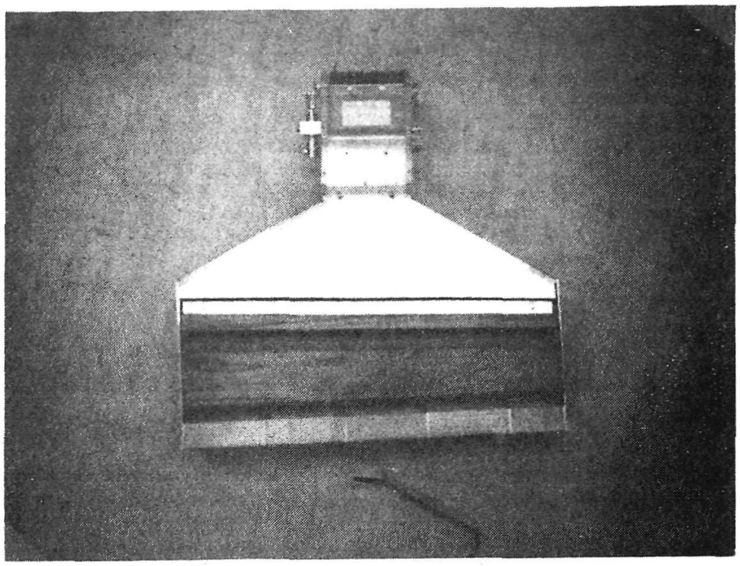


Figure ~~8~~ 6. Cascaded Amplifier Set for No. 3 Position (See Fig. ~~9~~ 7)

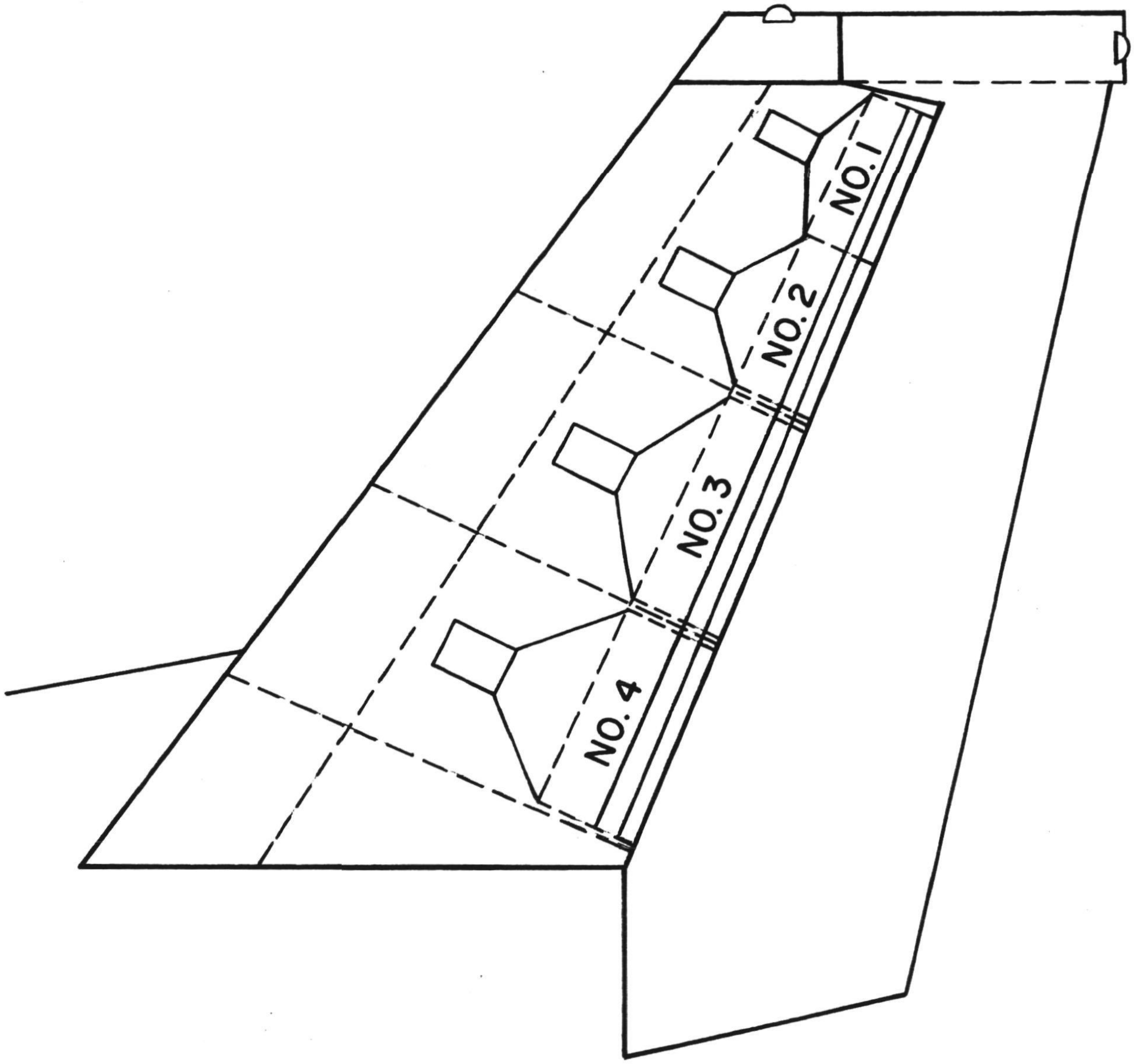
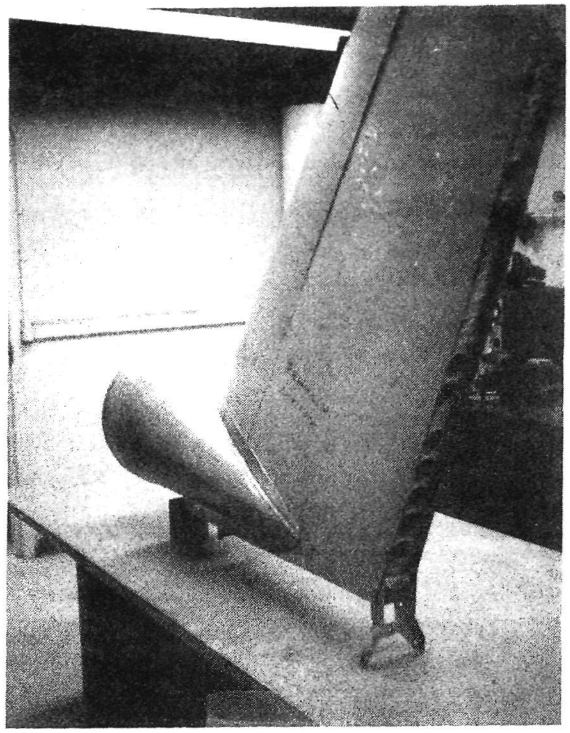
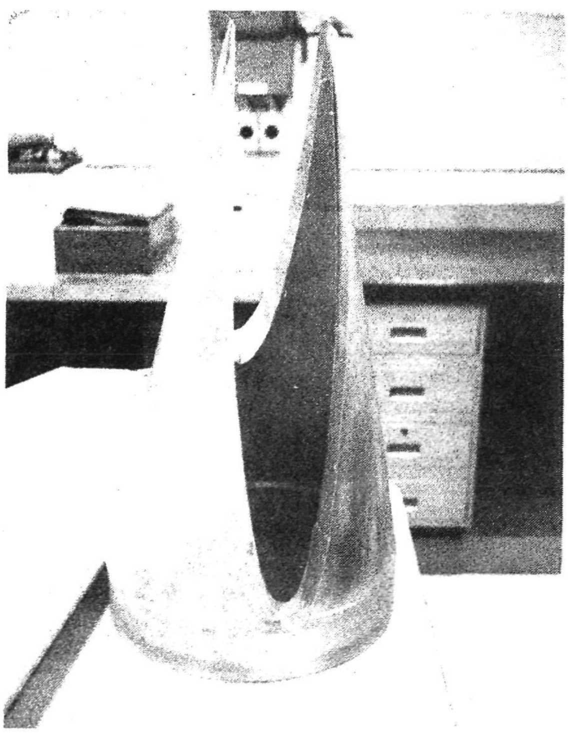
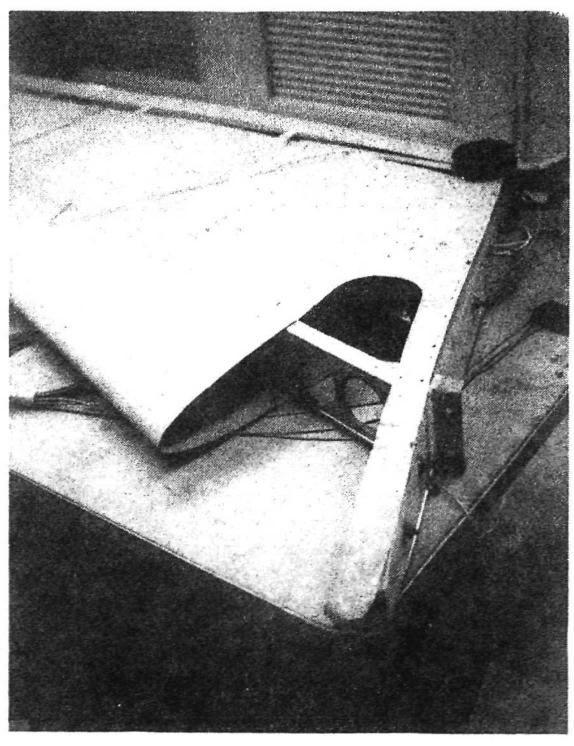


Figure 7. Layout of the Cascaded Amplifiers in the 172K Fluidic Rudder







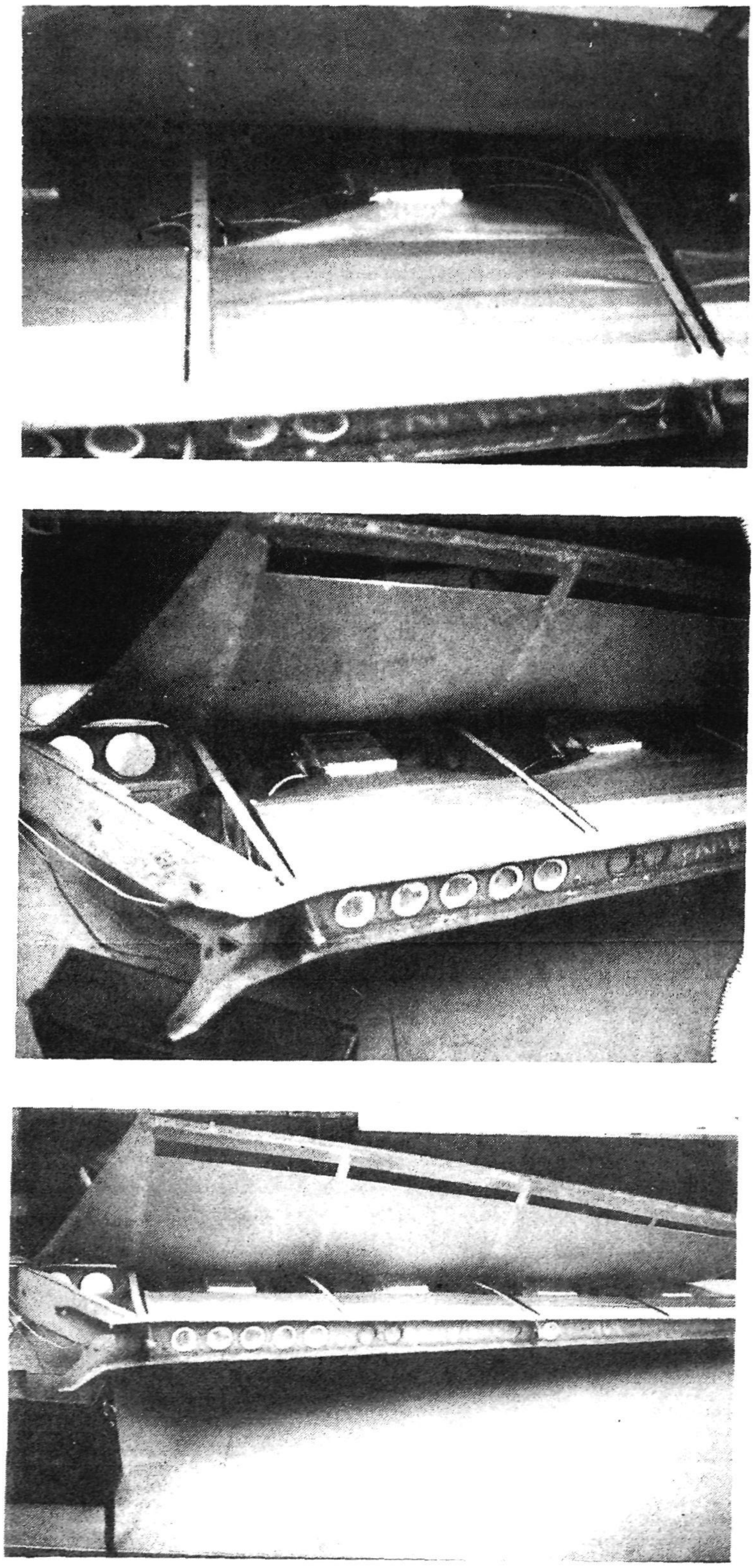


Figure ~~12~~ 9. (Continued) Details of the Assembly of the 172K Fluidic Rudder

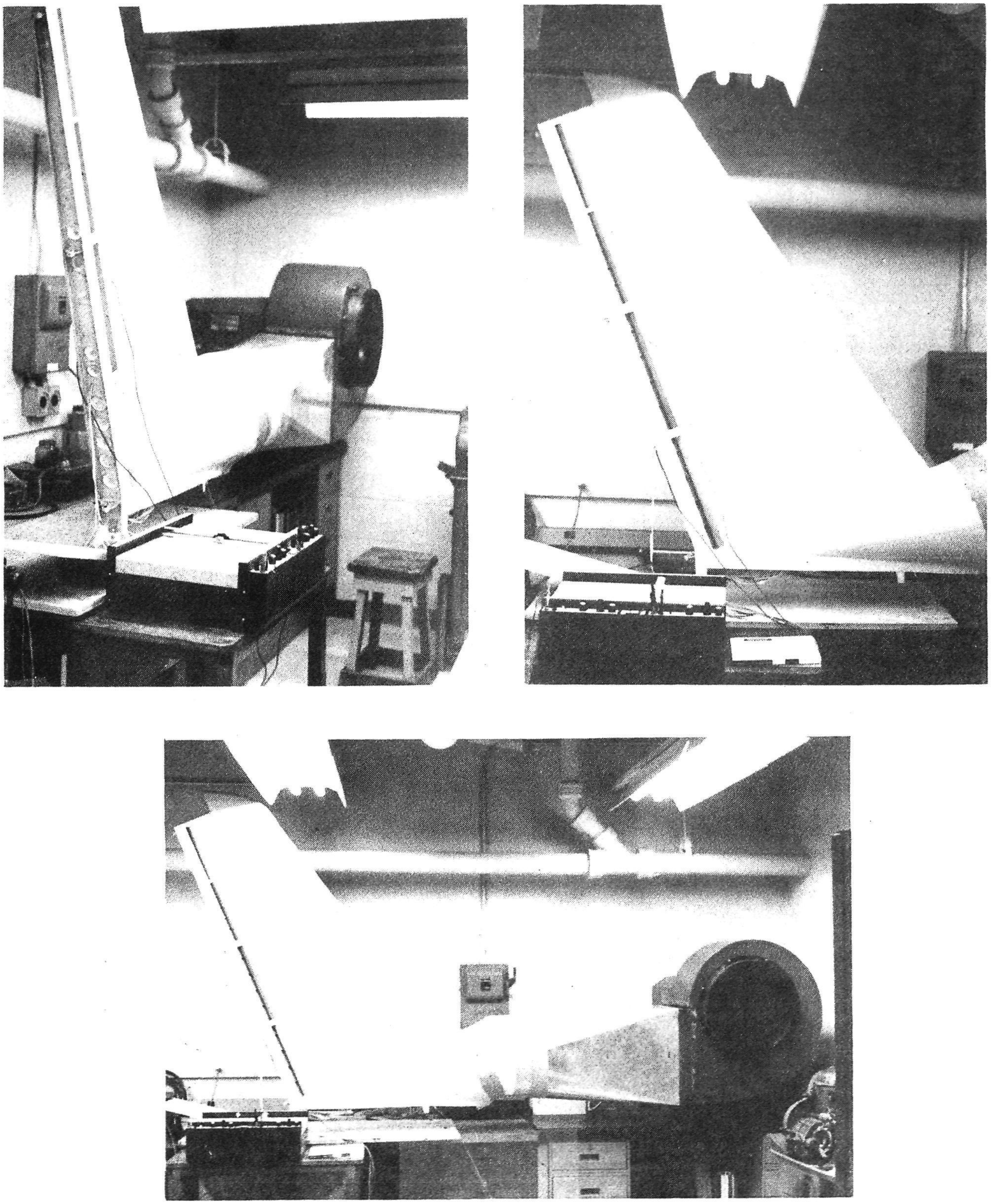


Figure ~~13~~ 10. Setup for Laboratory Tests

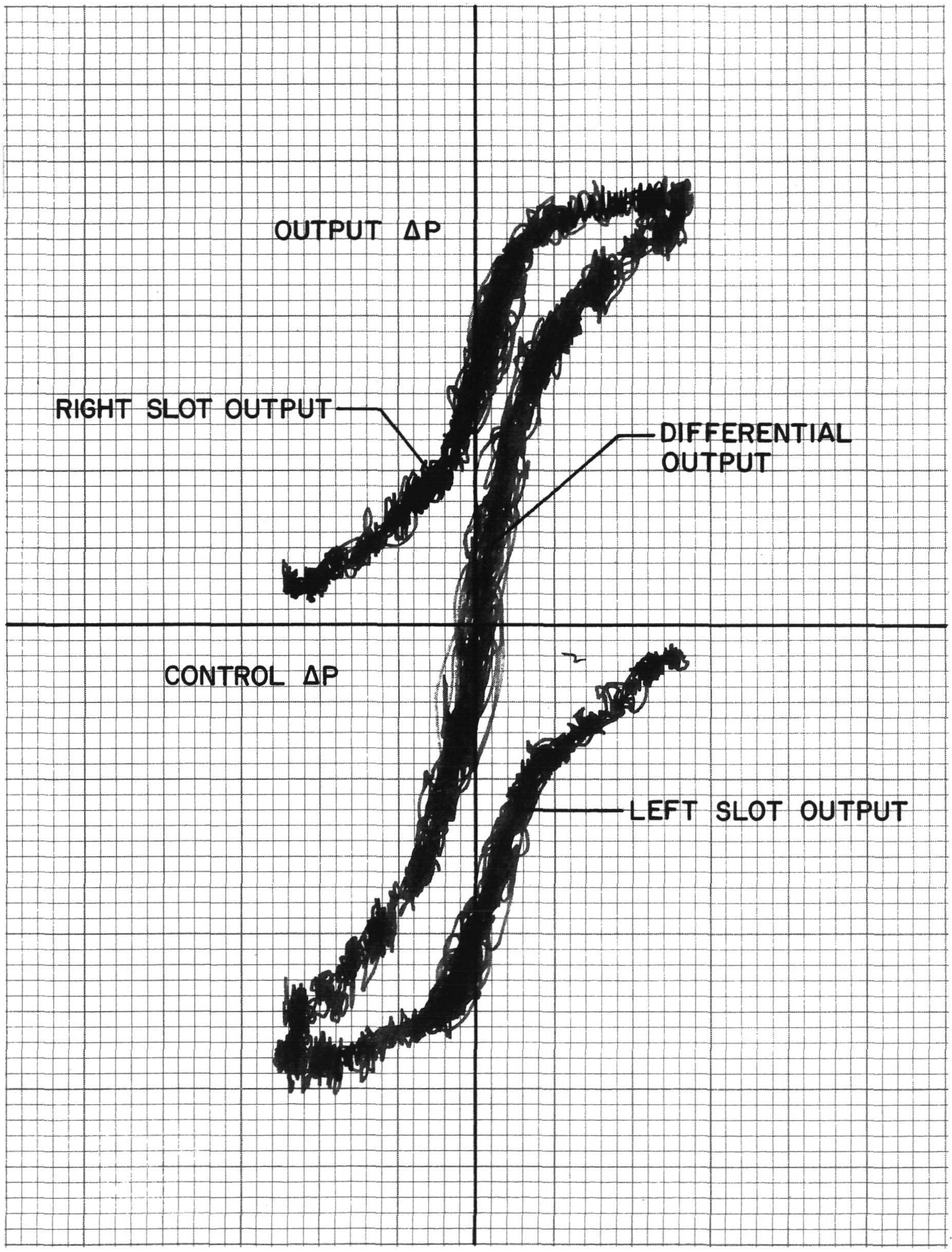


Figure 11. Characteristics of No. 3 Slot Flow Amplifier
(Equal Transducer Sensitivities)

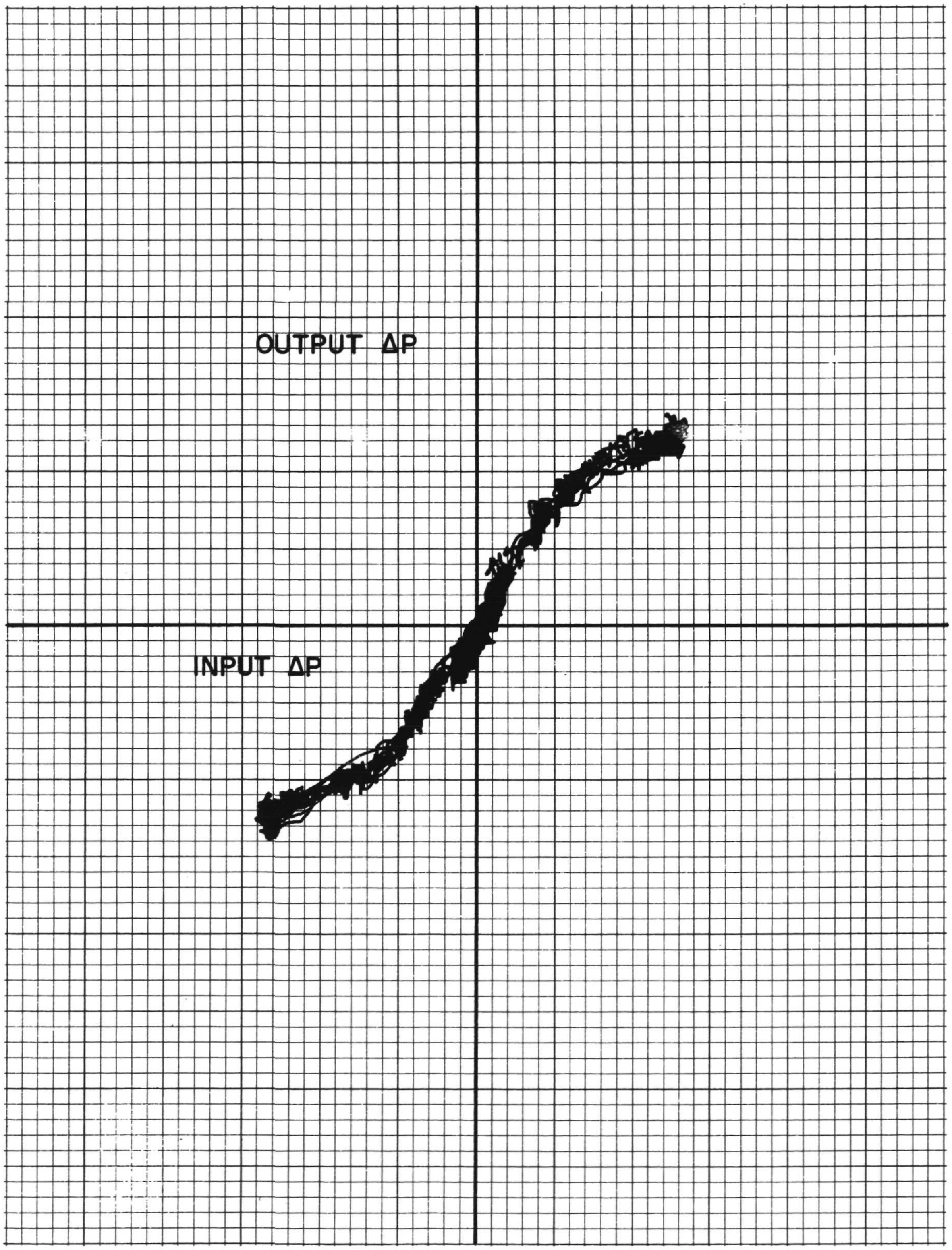


Figure 12. Characteristics of No. 3 Driver Amplifier
(Equal Transducer Sensitivities)

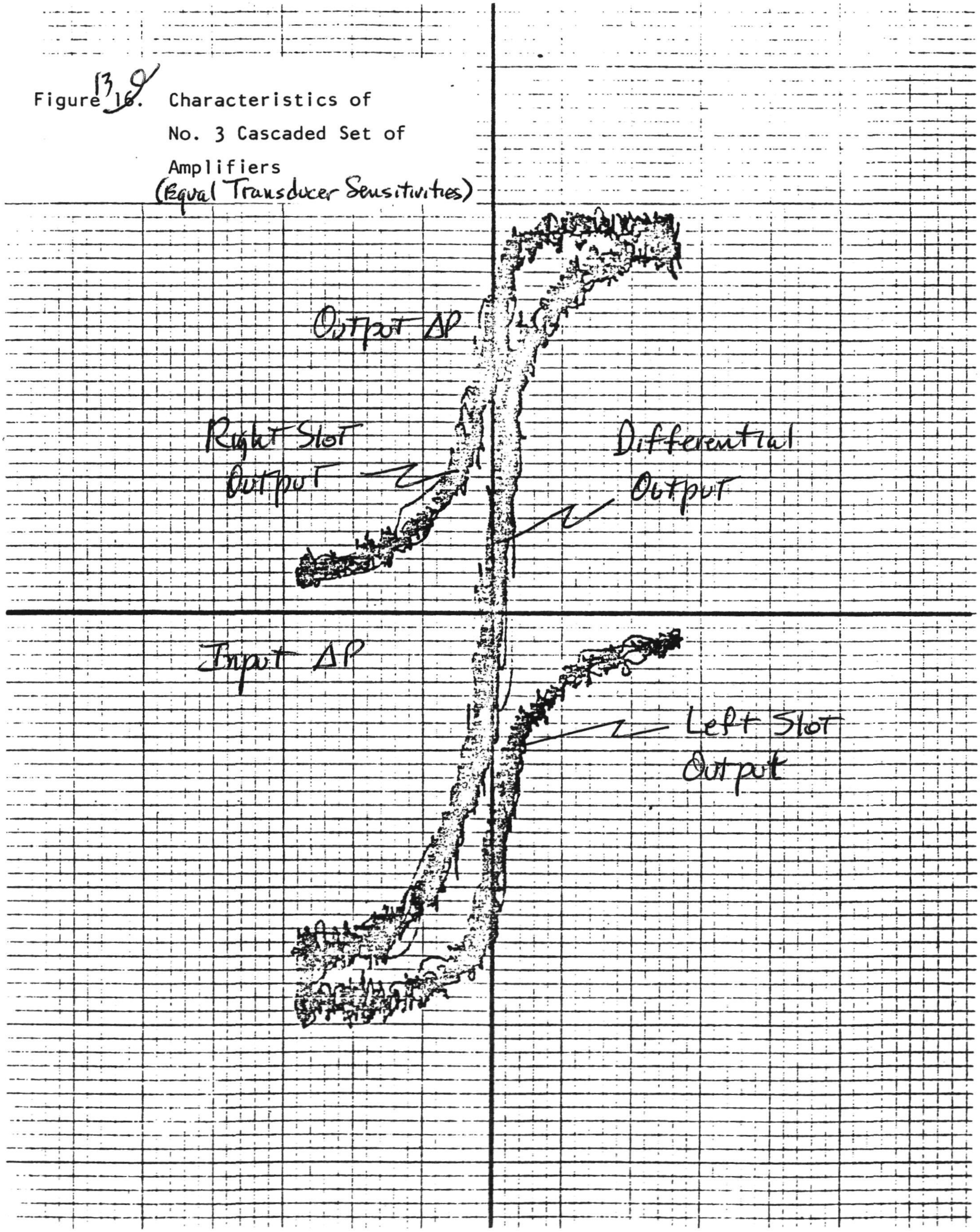


Figure ~~16~~ 13, 9. Characteristics of No. 3 Cascaded Set of Amplifiers (Equal Transducer Sensitivities)

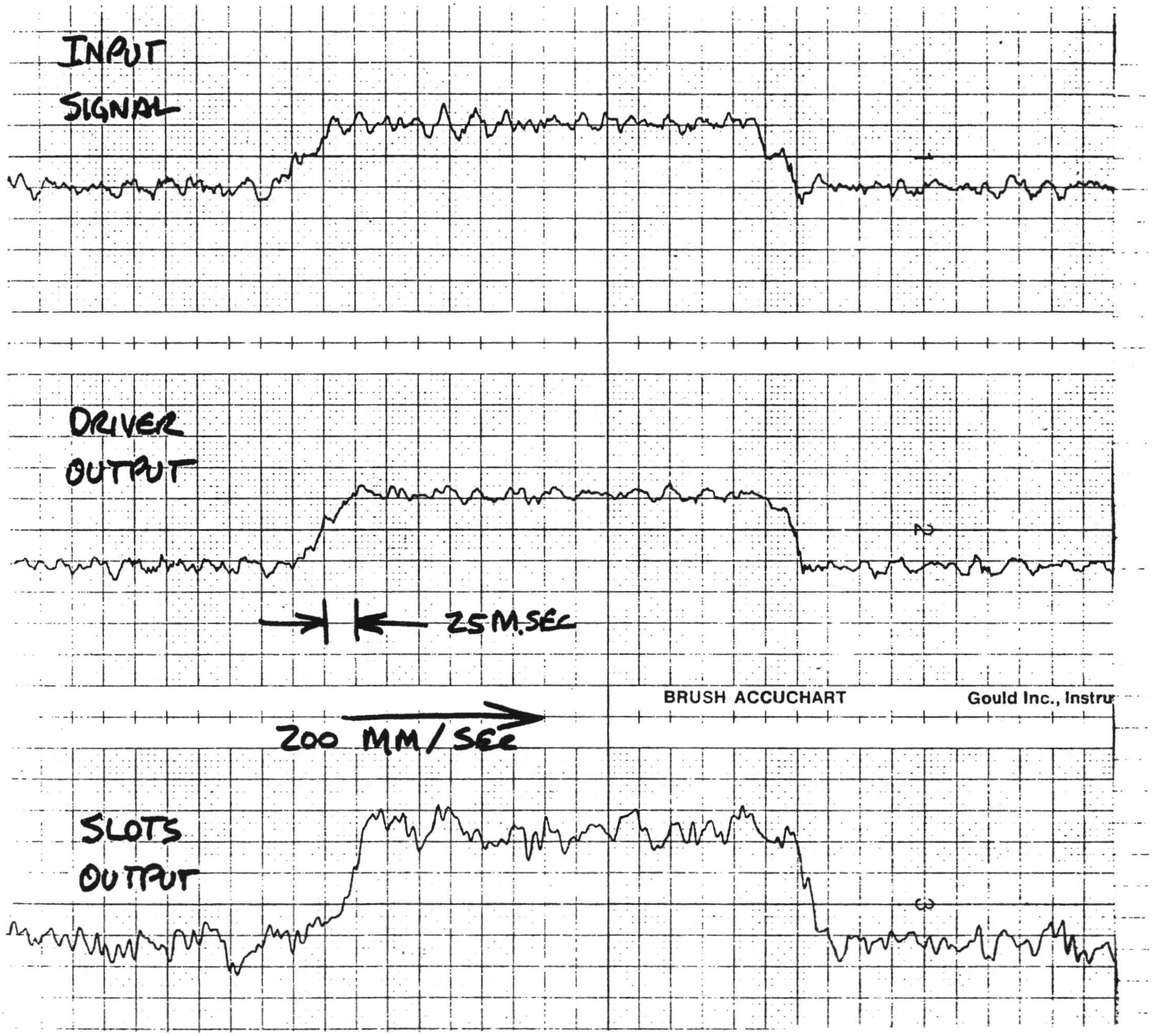
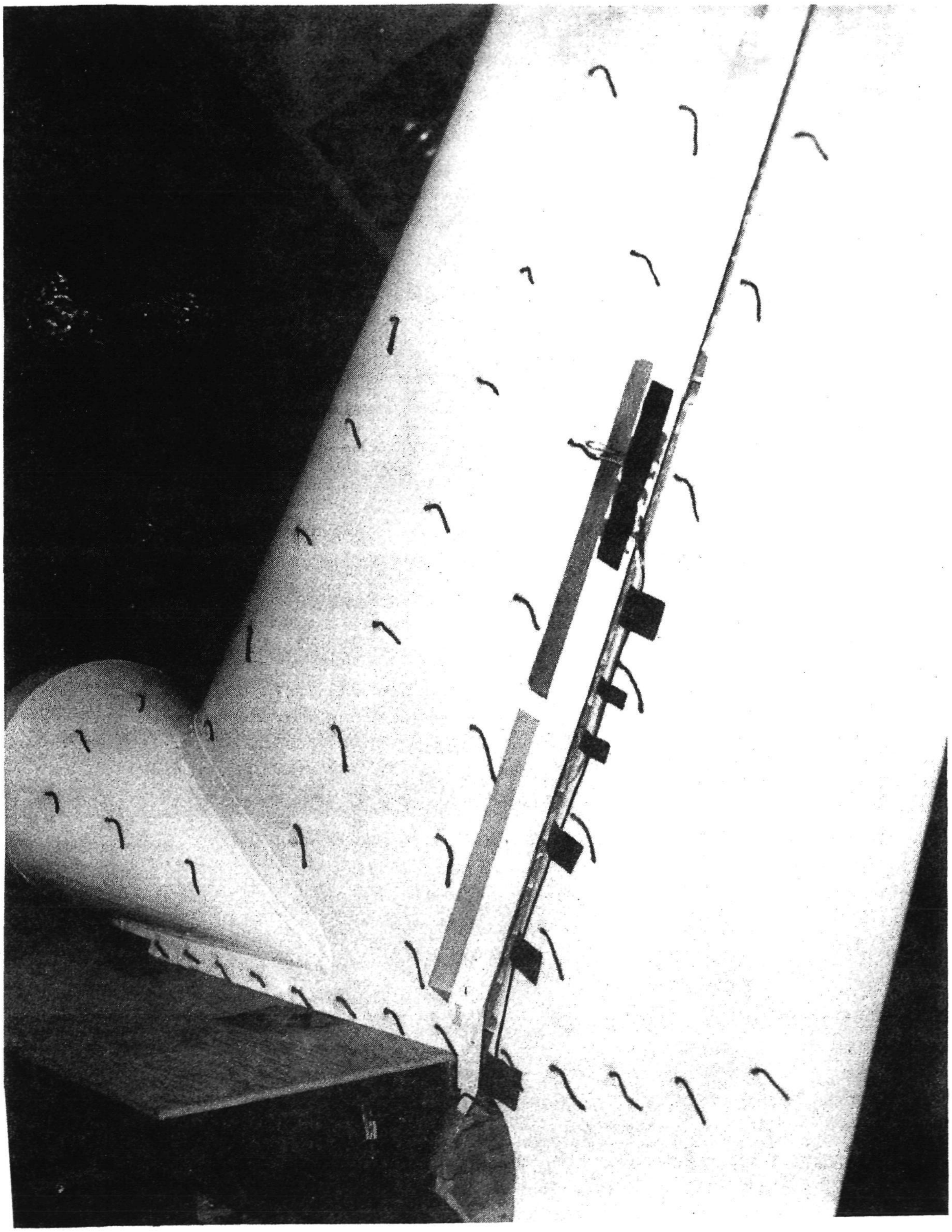


Figure 14. Dynamic Response of the Fluidic Amplifiers



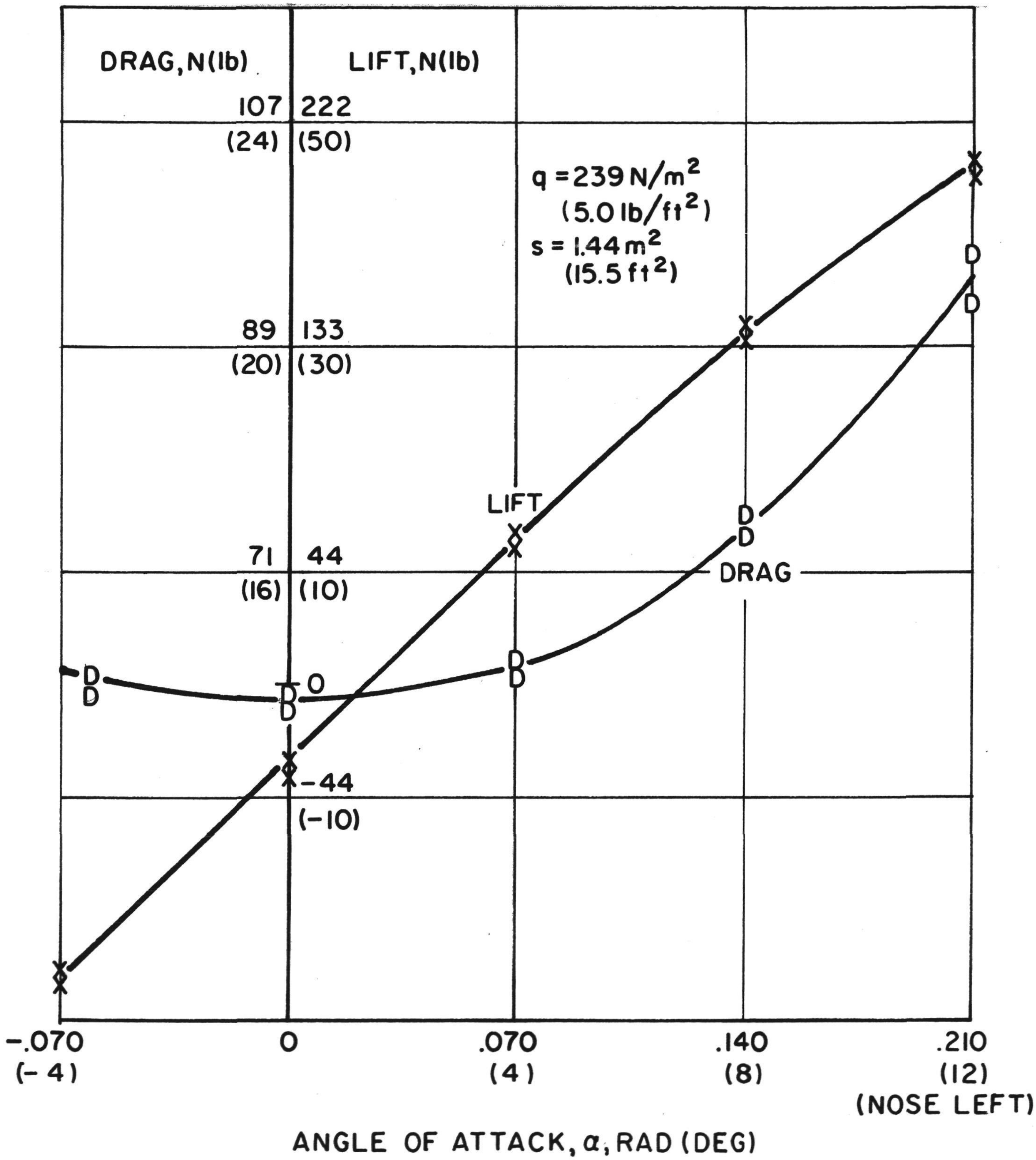


Figure 16. Characteristics of the 172K Vertical Tail Assembly
(Zero Rudder Deflection)

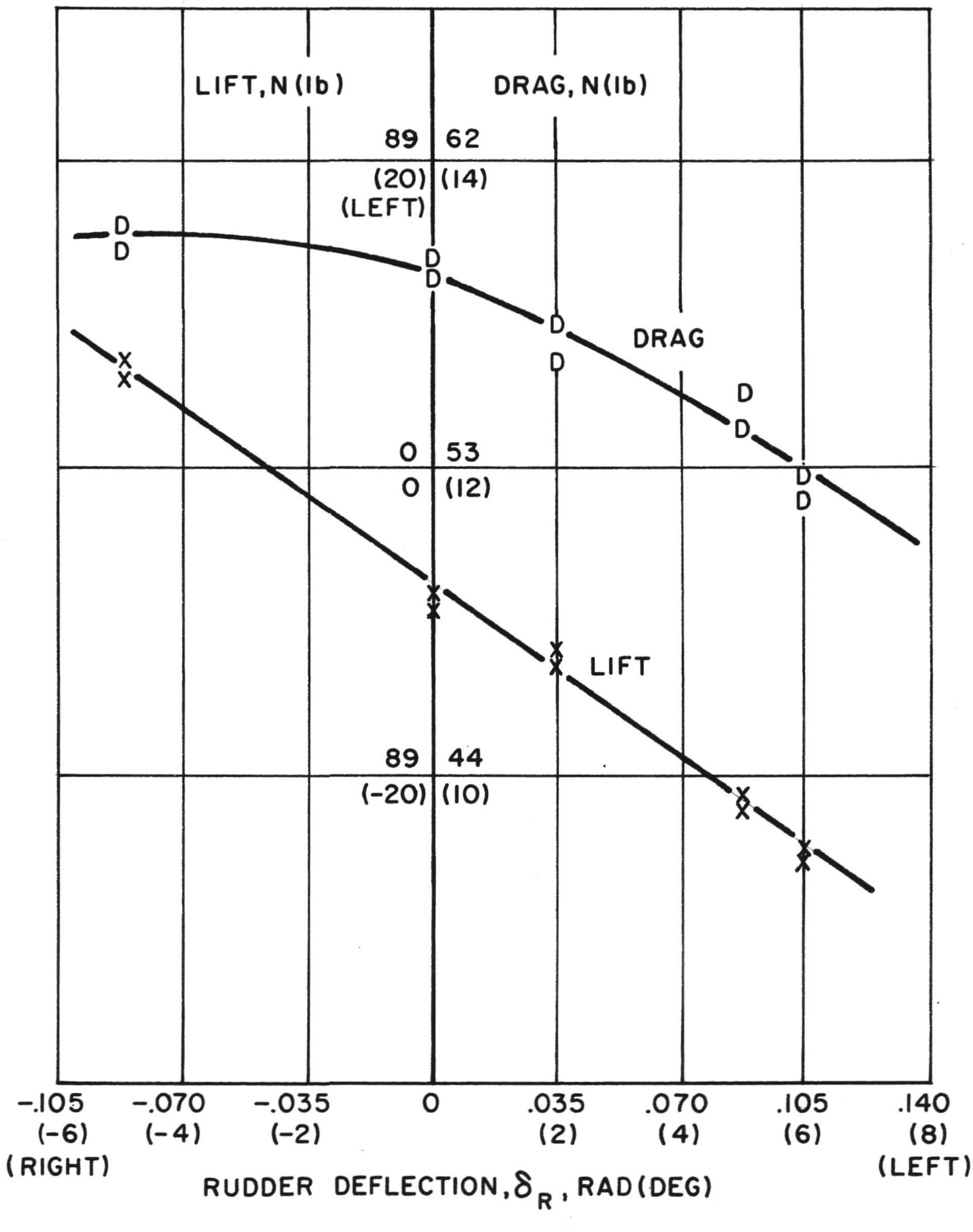


Figure 17. Effect of Rudder Deflection (Zero Angle of Attack)

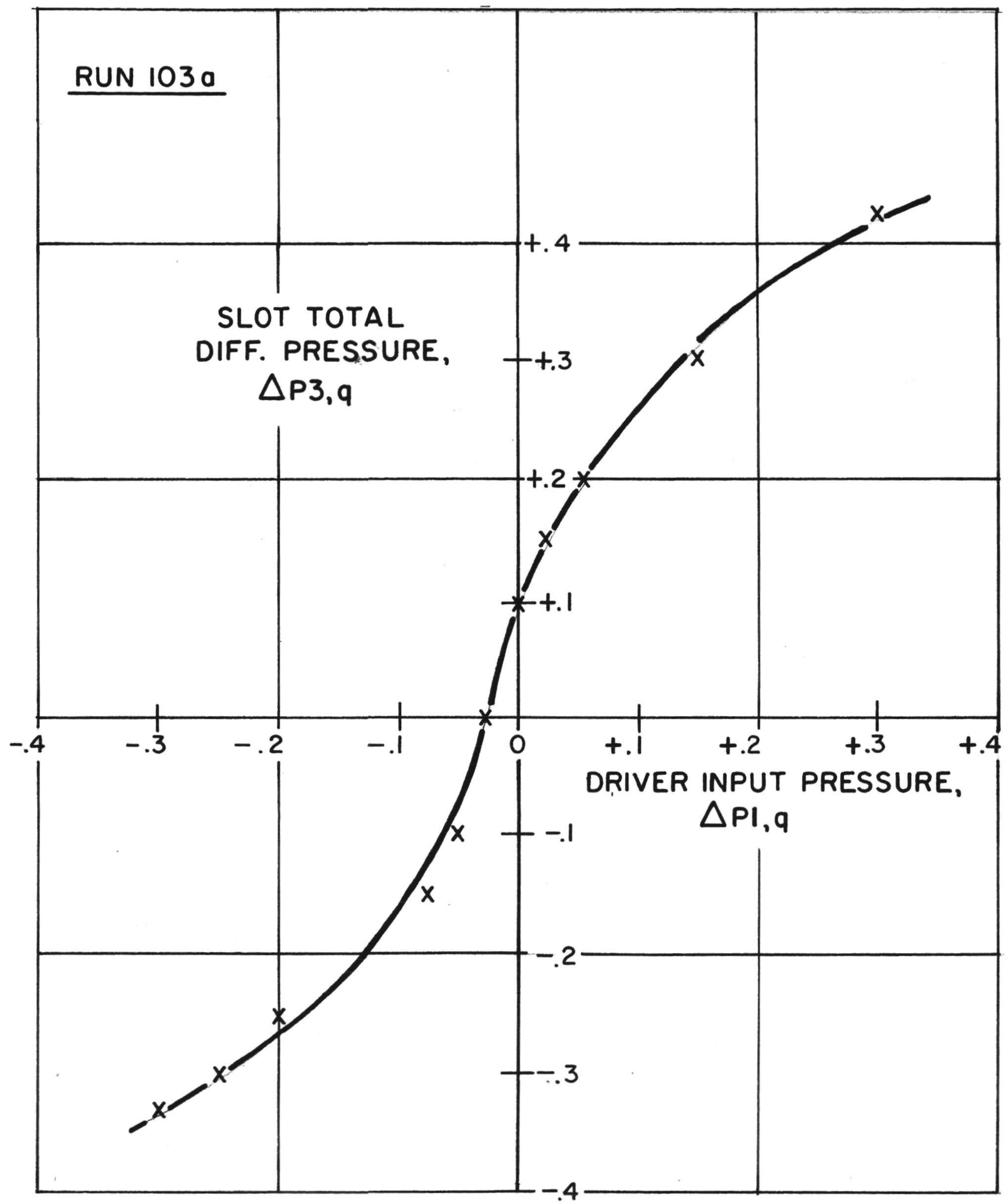


Figure 18. Overall Cascade of Fluidic Amplifiers

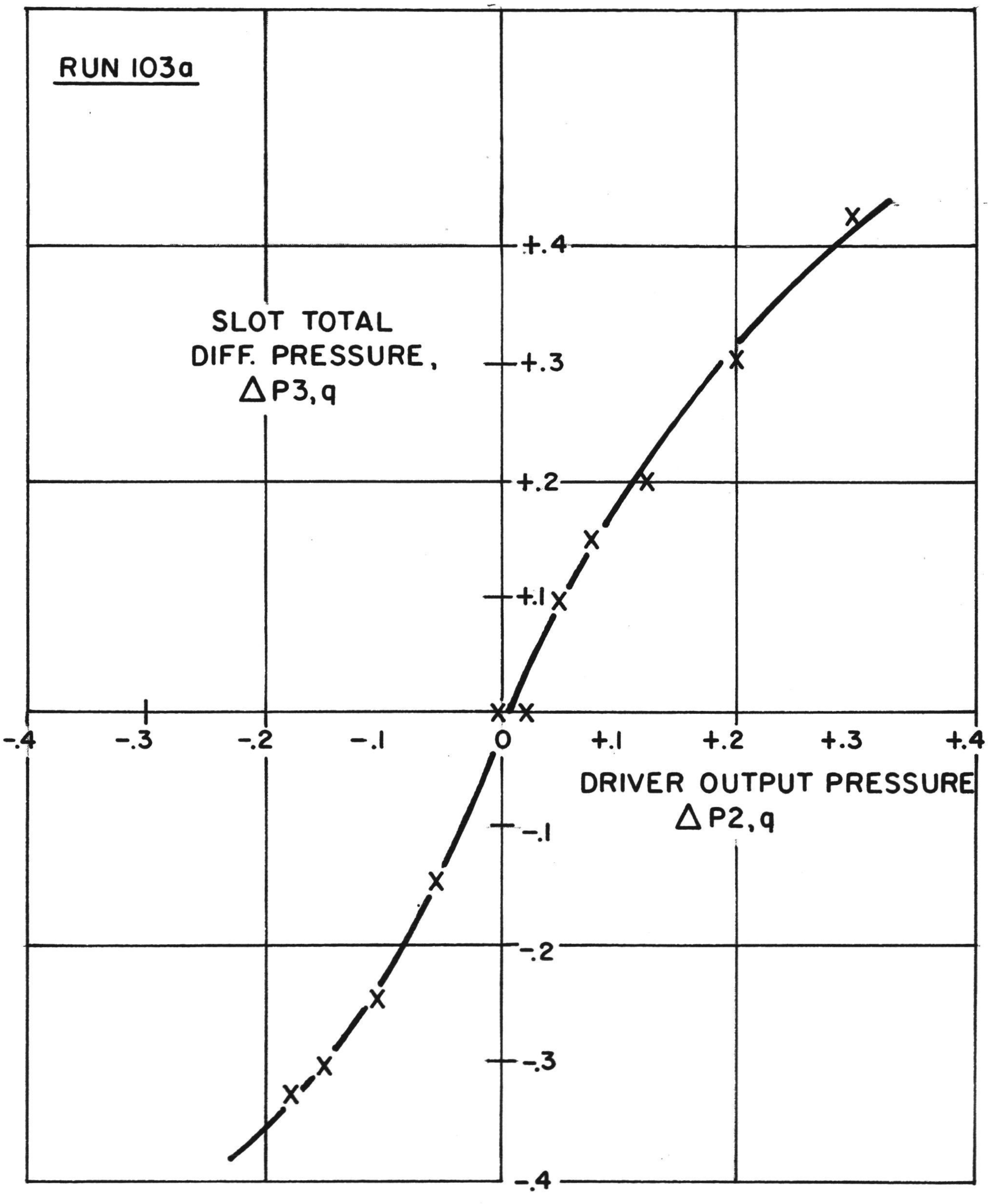


Figure 19. Characteristics of Slot Flow Amplifier

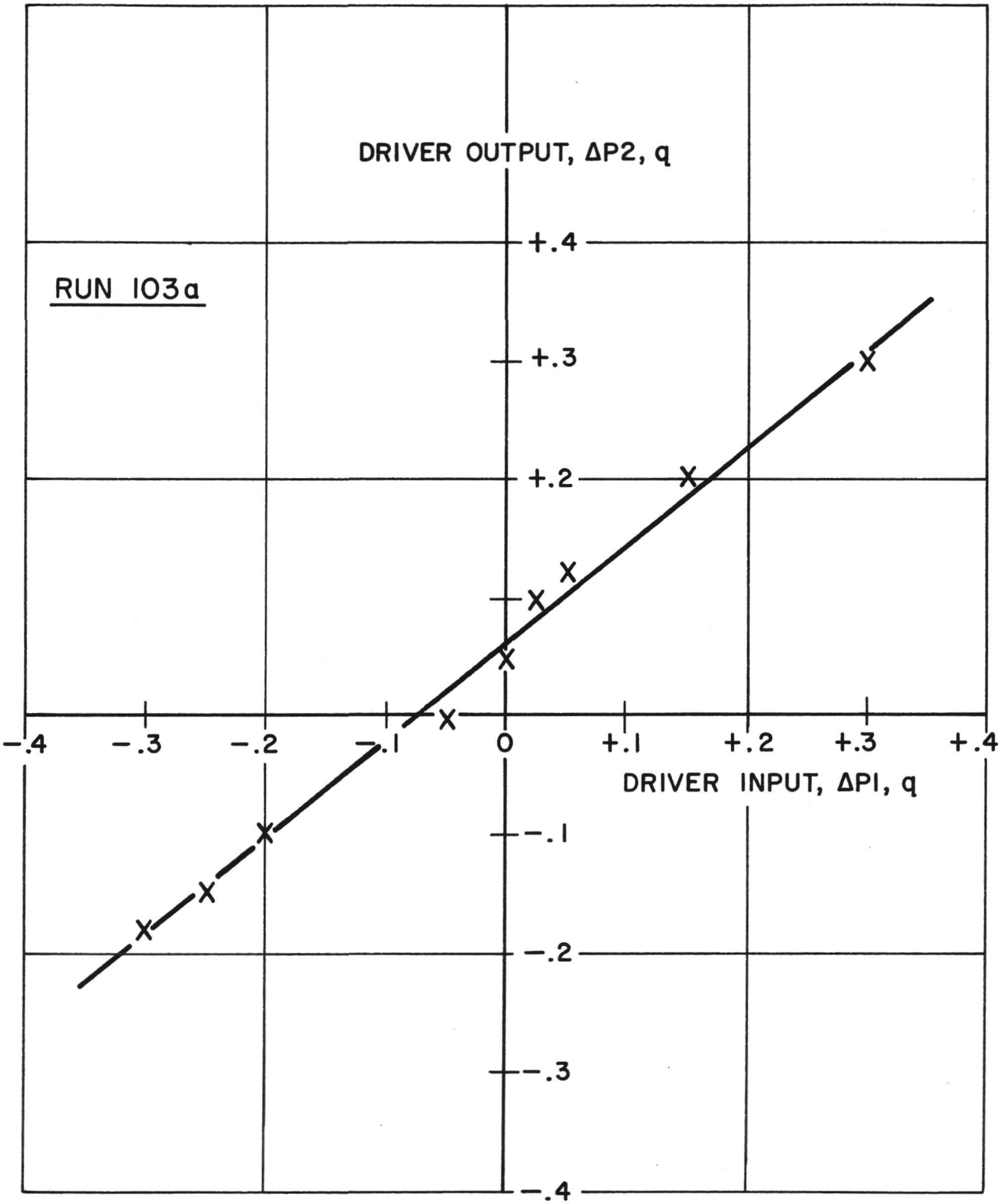


Figure 20. Characteristics of Driver Amplifier

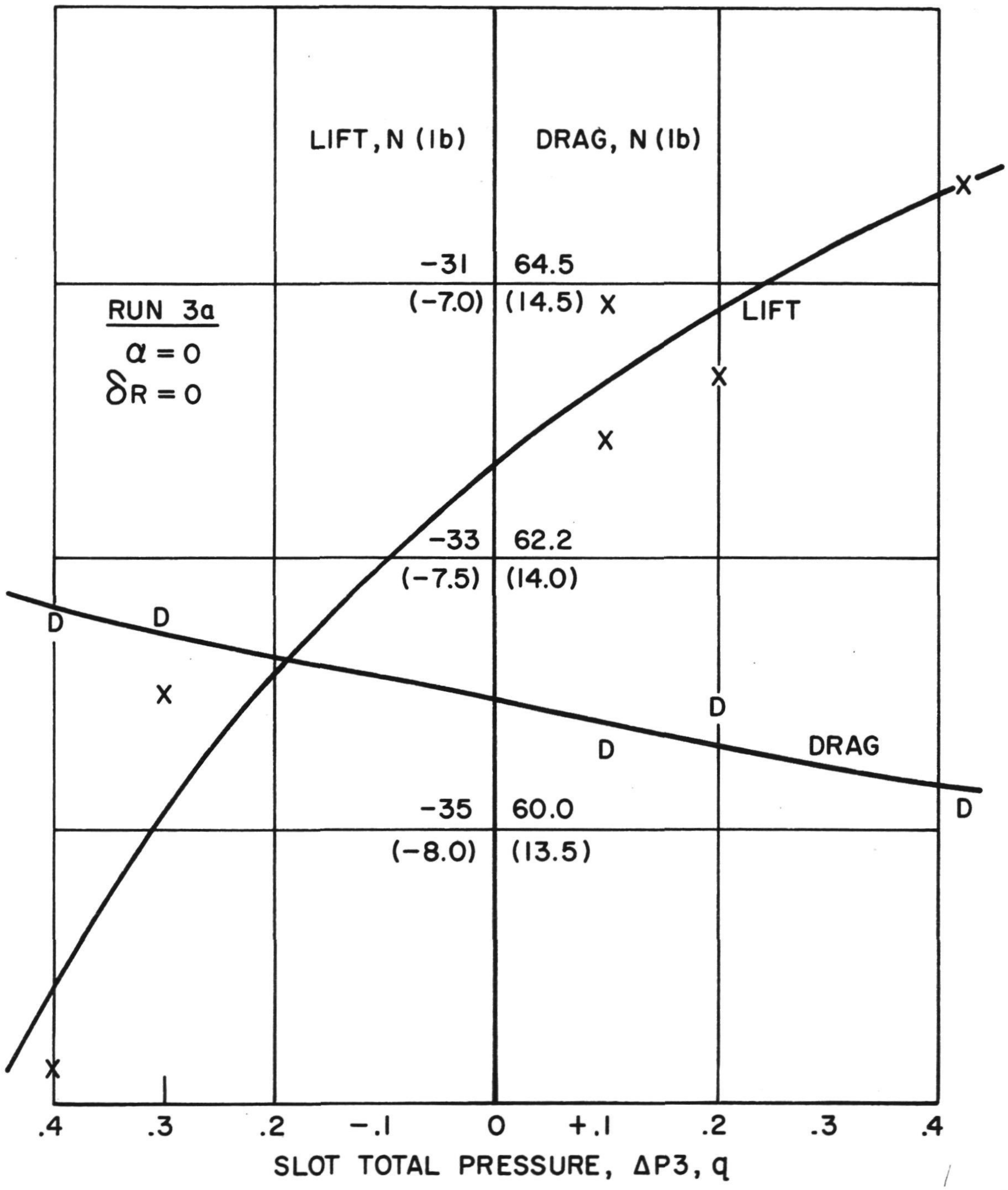


Figure 21. Airfoil Characteristics vs. Slot Flow

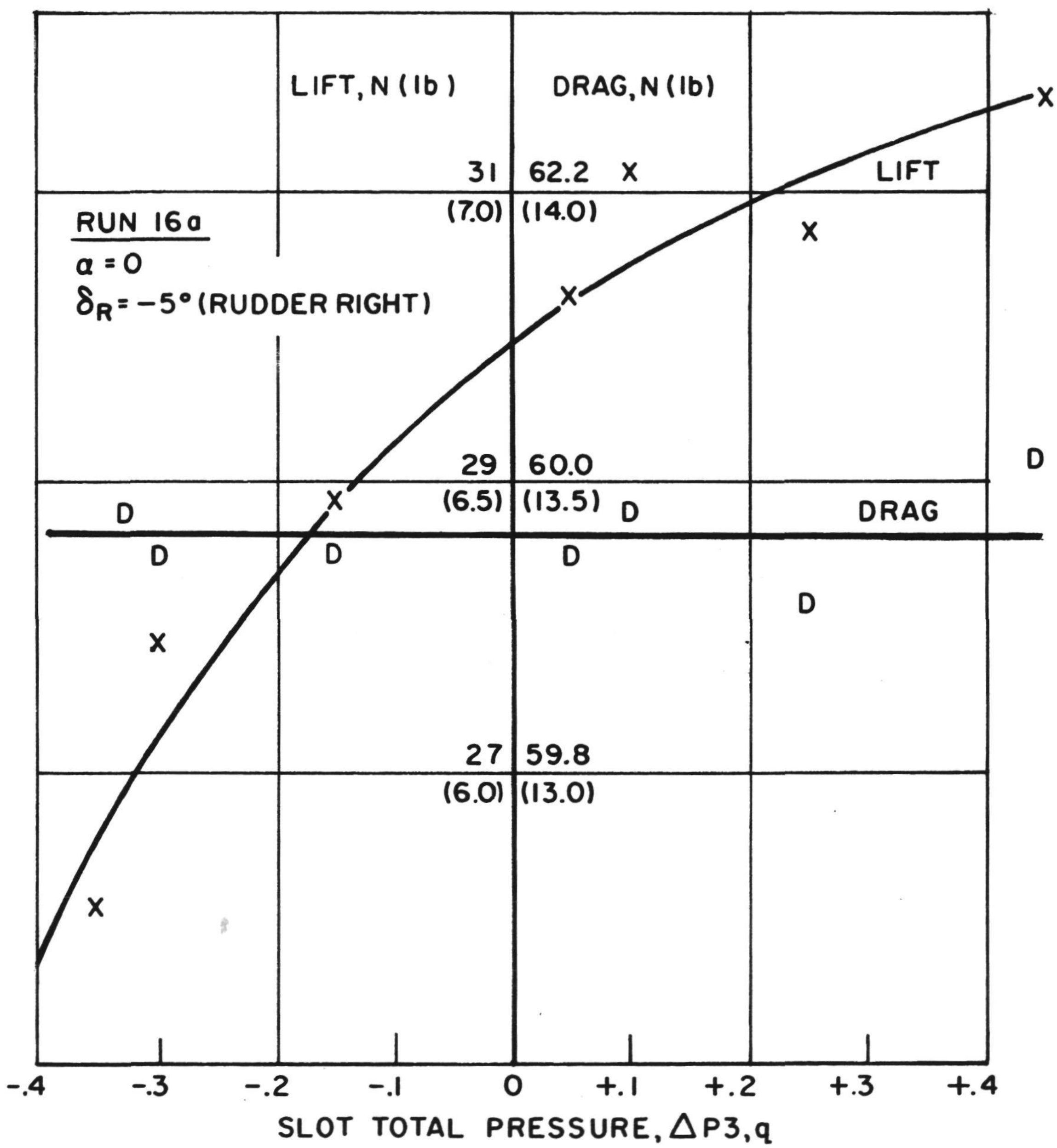


Figure 22. Airfoil Characteristics vs. Slot Flow

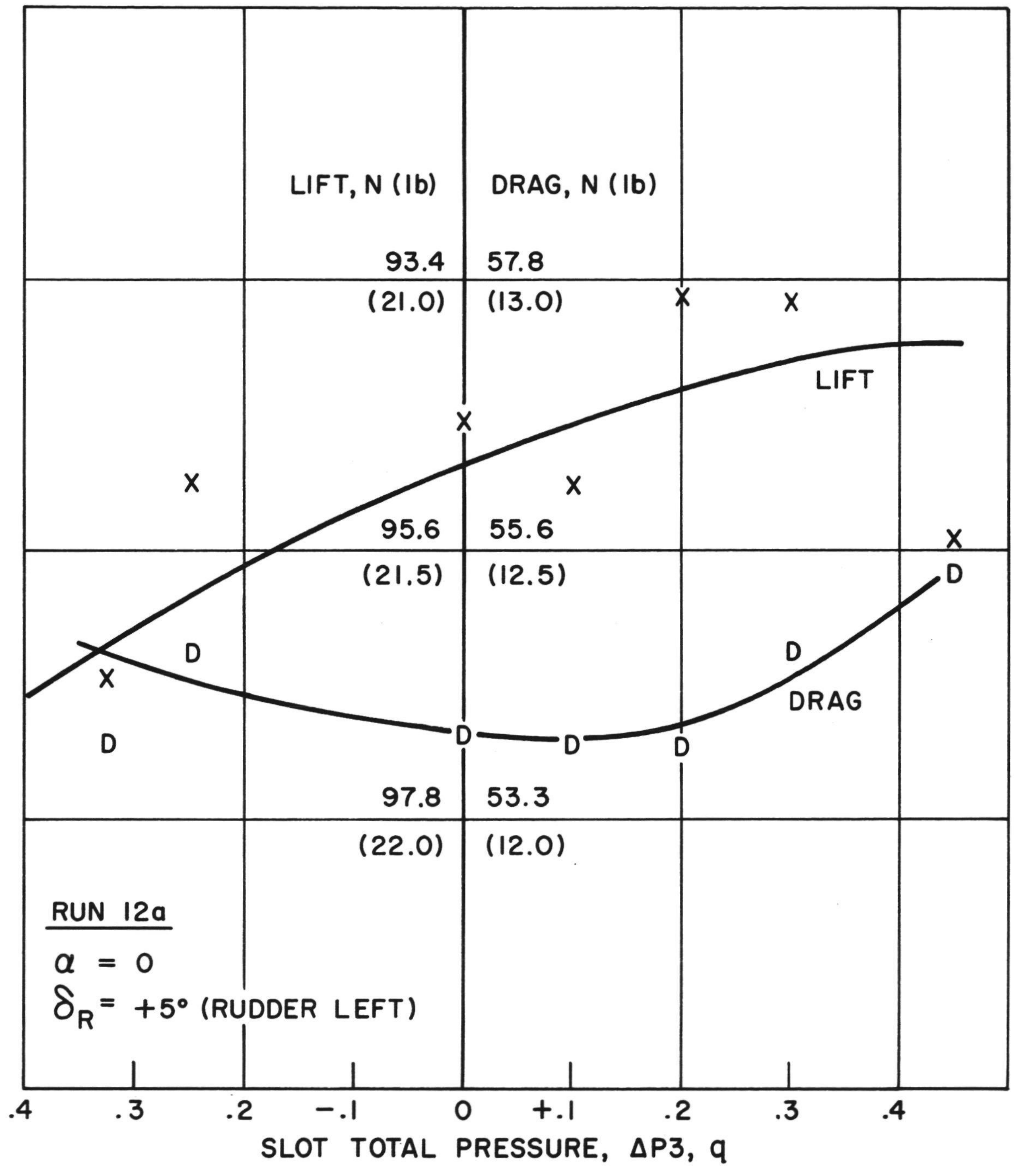


Figure 23. Airfoil Characteristics vs. Slot Flow

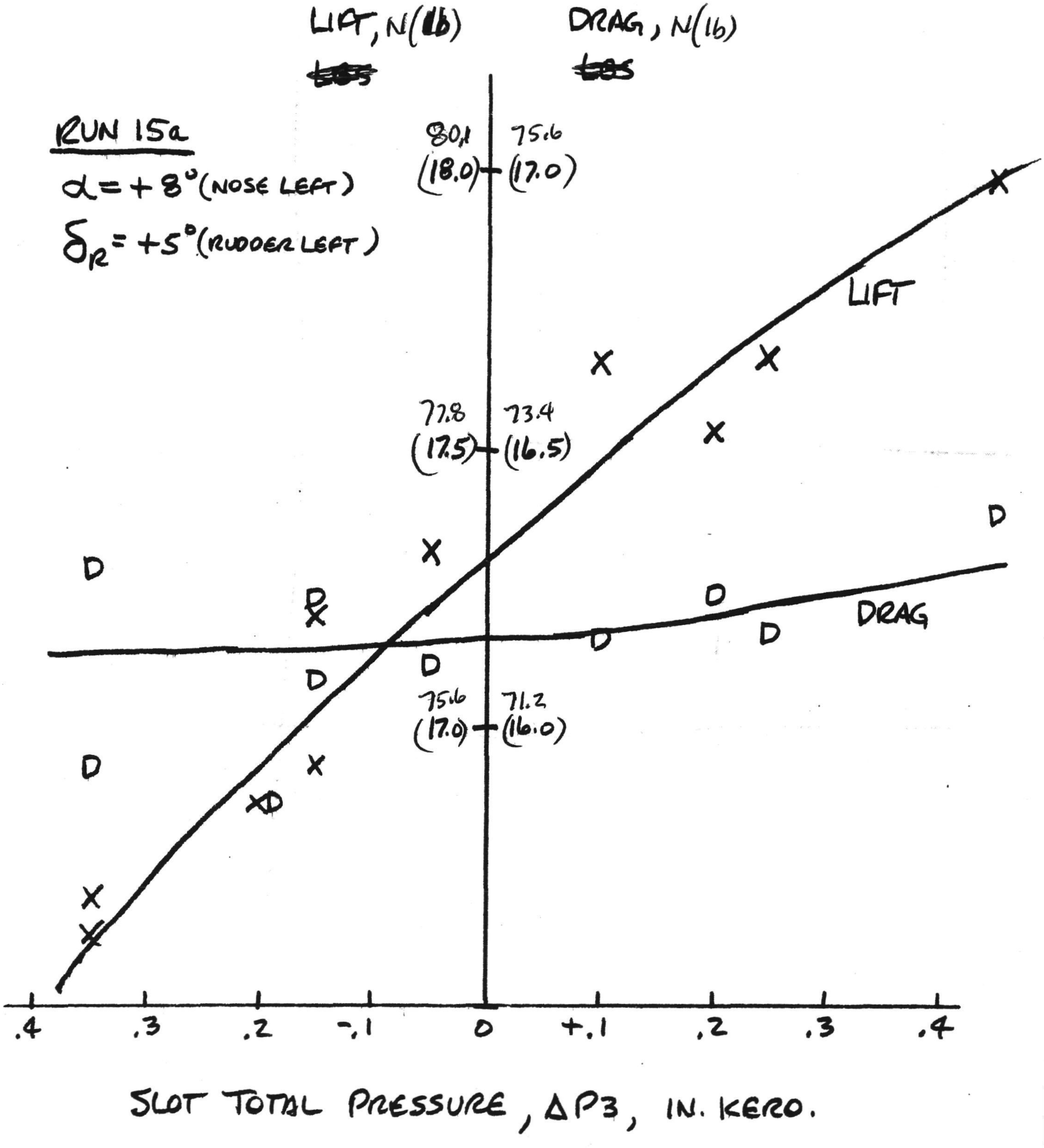


Figure ~~14.~~ 24. Airfoil Characteristics vs. Slot Flow

Figure ~~18~~ 25. Dynamic Response of the 172K Fluidic Rudder