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LOCKHEED MISSILES & SPACE COMPANY

HUNTSVILLE RESEARCH & ENGINEERING COMPANY

HUNTSVILLE RESEARCH PARK

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ELECTROFLUID CONVERTER STUDY

SEPTEMBER PROGRESS REPORT

Contract NAS8-11924

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Prepared for George C. Marshall Space Flight Center
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FOREWORD

This document contains a report of progress on the Electrofluid Converter Study, Contract NAS8-11924, which is being conducted by Lockheed Missiles & Space Company, Huntsville Research & Engineering Center, for the NASA/MSFC Astrionics Laboratory. The purpose of the study is to develop and demonstrate concepts for an electrofluid converter suitable for driving commercially available fluid amplifiers.

This report covers work accomplished during the period 25 August through 24 September 1965. Contributors to this report were Dr. C. S. Chang, G. O. Floyd, Dr. W. Trautwein, and J. E. Reich of the Huntsville Research & Engineering Center.

SUMMARY

Major effort continues to be in piezoelectric bender test and analysis, especially a trapezoidal shape. A deflectable splitter in a proportional fluid amplifier has been tested with moderate success. A pressure feedback system has been made operational. Tests indicate that the required flow change needed to drive a common proportional fluid amplifier full excursion of output can be provided by a simple flapper nozzle oscillating with amplitude modulated by an electrical command.

DISCUSSION

Mechanical Configurations

Deflectable Splitter: The test device with a manually operated deflectable splitter as shown in Figure 1 of Reference 1 was completed and the first series of tests was run. A hot wire anemometer was used for sensing the velocities at both outlets of the two leg device.

Typical outlet velocity values vs the channel width at the splitter's leading edge are plotted in Figure 1 of this report. The saturation effect observed in the right outlet was most likely due to separation of the flow from the right splitter wall caused by a sharp edge. Additional tests are being run with an improved splitter to avoid this saturation effect.

In the left leg which performed more linearly, a mean gain (velocity difference per unit splitter nose deflection) of

$$K_V = 250 \frac{\text{ft/sec}}{\text{in.}}$$

was measured. Under the laws for incompressible flow this results in pressure gains of

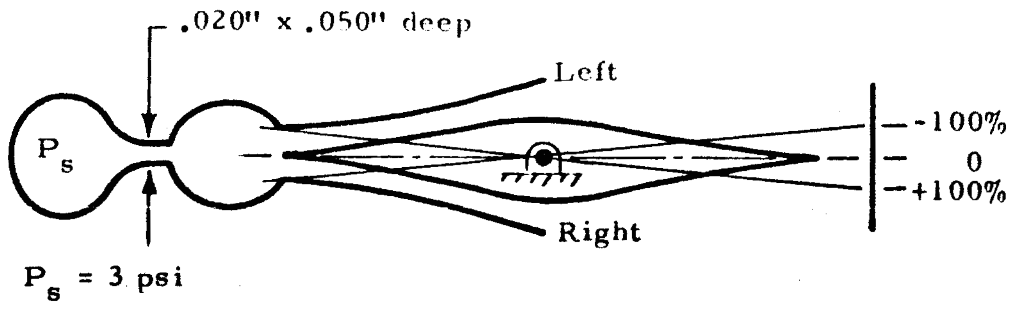
$$K_P = \frac{\rho}{2} K_V^2 .$$

With a standard air density of 0.00238 slugs/ft^3, this yields 0.516 $\frac{\text{psi}}{\text{in.}}$.

When a piezoelectric bimorph connected in parallel with .75-inch free length and a ratio of deflection-to-input voltage of

$$2 \times 10^{-5} \text{ in./V}$$

is used as splitter, pressure output gains (differential pressure per unit input voltage) of 1.03×10^{-5} psi/V are feasible. With maximum input voltages of ± 300 V this yields pressure signals of $\Delta P_{max} = \pm 0.0031$ psi.



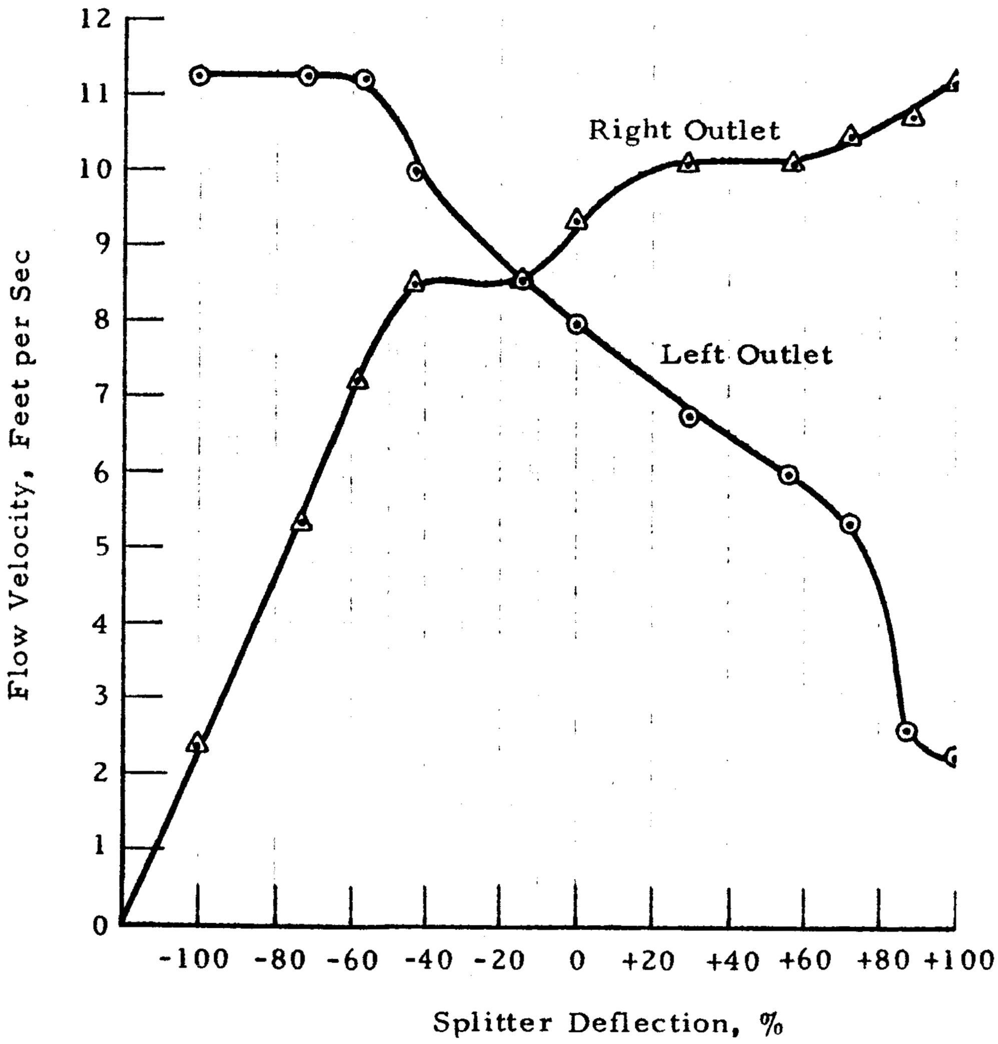


Figure 1 - Deflectable Splitter, Flow Velocity vs Deflection

For driving standard proportional fluid amplifiers, higher control pressures are desirable. Therefore, several changes in the channels and splitter of the test device are being made to increase maximum output signals.

Movable Nozzle: In view of the great improvement in performance of the trapezoidal over the straight piezoelectric forms and of the basic difficulty of maintaining smooth, well-sealed surfaces in the deflectable splitter, the movable nozzle appears somewhat more attractive than the deflectable splitter. The movable nozzle and its manual test device were discussed and illustrated in Reference 1 (Page 1 and Figure 2). Design of the test device will proceed immediately, now that some experience has been gained in the deflectable splitter.

Flapper Valve: The flapper valve approach under development would control air entering the control port of a fluid amplifier by varying the amplitude of oscillation of a flapper proximate to a valve opening. A discussion of the flapper valve concept is also given in the August progress report, Page 3. The flapper will most likely be a simple piezoelectric bender operating at its resonant frequency. This method of operation should minimize many of the non-linearities characteristic of piezoelectric, e.g., hysteresis and creepage with time. The nozzle and flapper will be built with a minimum volume and mounted directly on or within the control inlet of the fluid amplifier to minimize operational time delay (see Figure 2).

To obtain practical experience and operational data, a test setup was made (see Figure 3). A pointed nozzle with 0.021-inch diameter hole was tested at various values of L and quiescent flows*, Q_Q. As seen in Figure 4 , percent change in flow is greatest at the highest supply pressure, P_s, used. A higher test supply pressure was considered of little interest since in operation, common fluid amplifiers do not require pressures, so none would be available in practical application.

*quiescent flow is defined as that when the flapper is still.

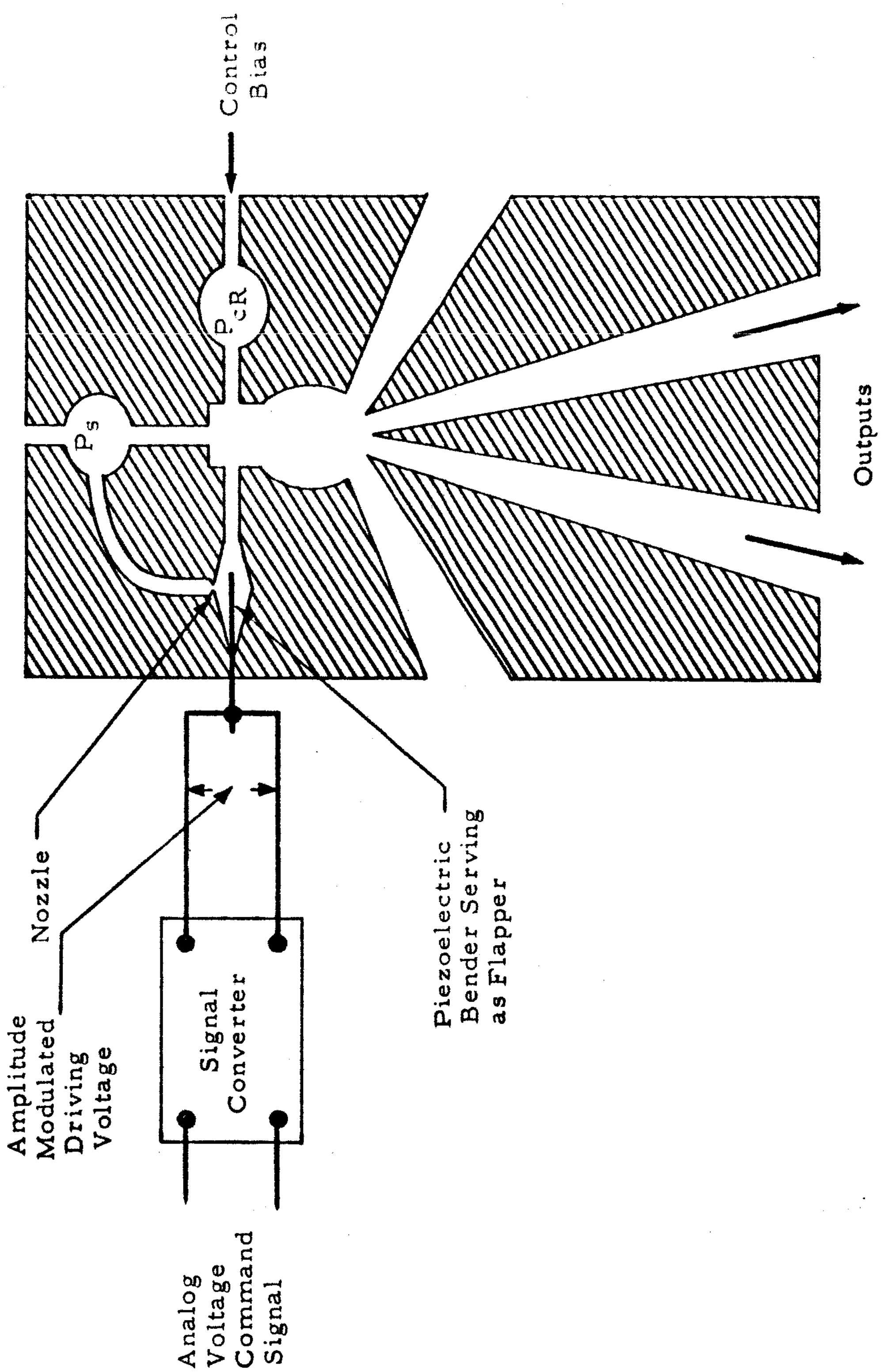


Figure 2 - Application of Flapper Valve as an Electrofluid Converter

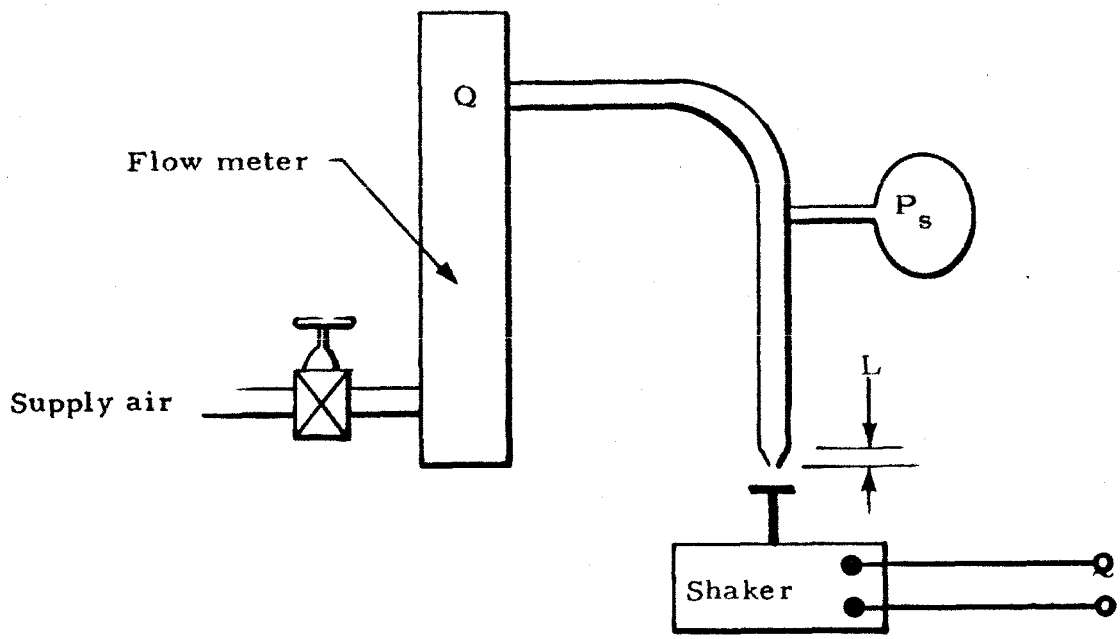
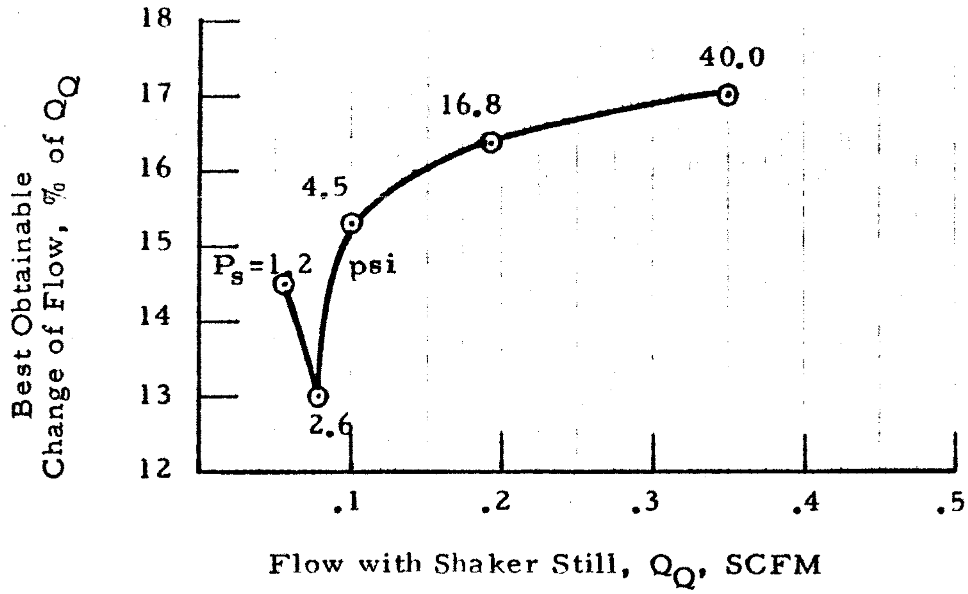


Figure 3 - Flapper Valve Test Setup

The highest change of flow rate producible by the setup was 0.06 scfm. At the absolute flow rate about which the change was measured, (approximately 0.35 scfm) a change of flow rate of 0.10 scfm is required to drive one common proportional fluid amplifier through its full excursion. This value was obtained by test. It is recognized that the flow impedance during tests are somewhat different from that seen at the amplifier control port. This difference would alter the value of pressure at which the converter operates. But with a vented amplifier and relatively low flows in comparison to control nozzle area, flow alone is considered a practical criterion for initial converter design.

A practical nozzle-flapper design will be made and proven. It will be designed with sufficient flow to drive the proportional fluid amplifier mentioned above, or possibly a smaller one instead. Then the shaker will be replaced by a piezoelectric flapper of a configuration which can be packaged in the working device. After this is proven, a complete working model will be built.



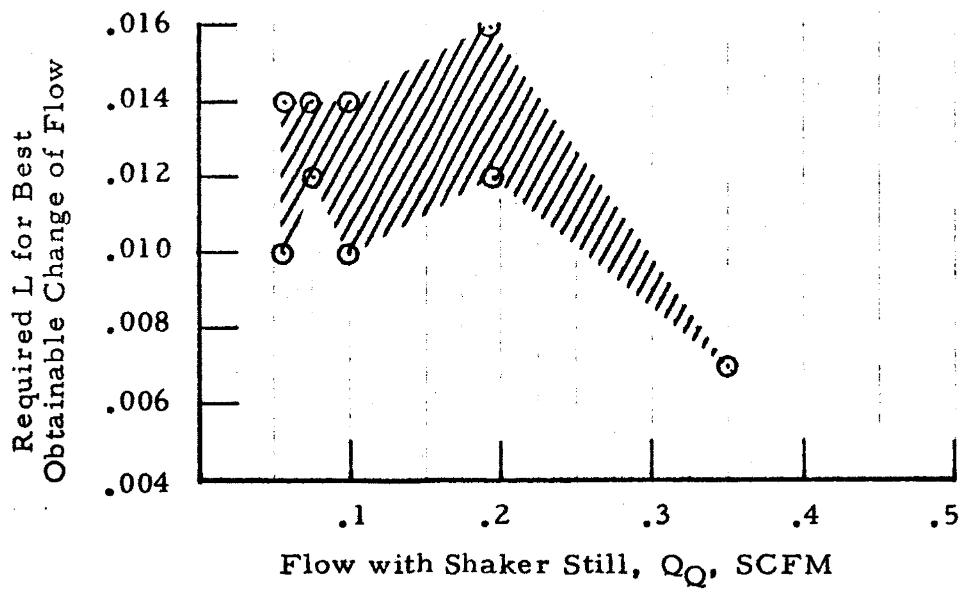


Figure 4 - Characteristics of Flapper Valve

DEFLECTION MOTIVATION

Piezoelectric

Further Test Results: In order to get sufficient data for layout and design of an electrofluid converter using piezoelectric benders, additional tests were run with the instrumentation described in the last progress report (August report, Figure 4). The tested benders of trapezoidal shape with dimensions shown in Figure 5 are best suited for deflectable nozzle configurations as shown in Figure 10 of Reference 1.

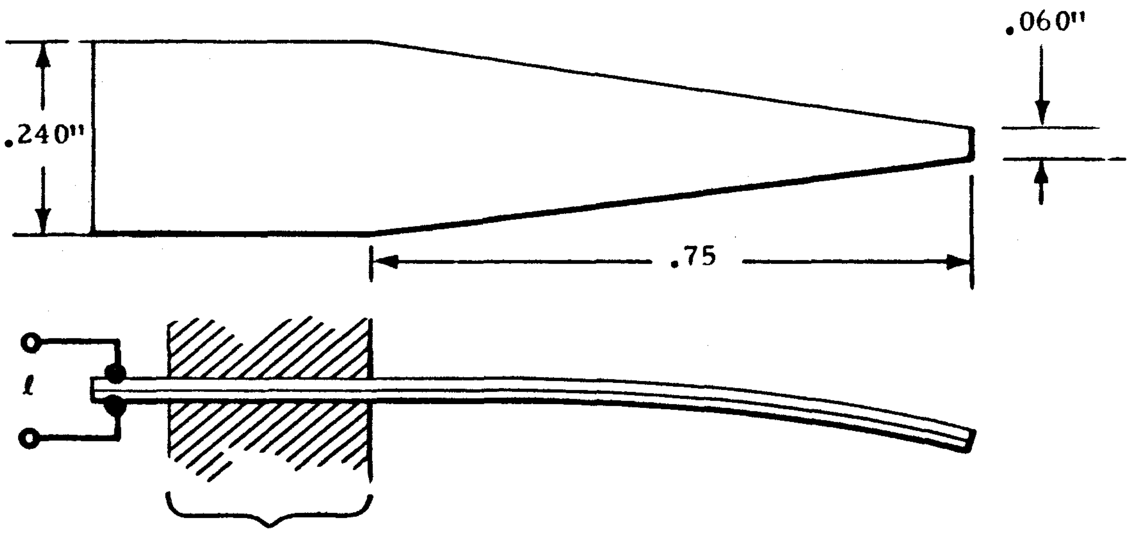


Figure 5 - Dimensions of Tested Piezoelectric Bender

The properties of the trapezoidal benders to be determined by the tests were:

- Frequency response
- Gain (ratio of deflection/input voltage)
- Linearity of deflection versus input voltage
- Creepage when dc voltages are applied during long time periods
- Hysteresis at various frequencies.

Comparisons with the performance of parallel benders as tested in August show that both frequency response and gain of the trapezoidal probes are superior. Figure 6 shows a typical deflection versus frequency plot; Figure 7 gives the deflections for dc inputs. At the maximum voltage of 400 Vdc a second reading was made after five minutes with an increase in deflection due to creepage of 5%. Comparing the 140 Vdc deflection of Figure 7 with the deflections in Figure 6 at low frequency, and equal peak voltage of 140 V indicates a considerable amount of creepage in the low voltage range, as the deflection due to the dc input in Figure 7 is about 80% higher than the comparable ac response. Further investigations are necessary to determine creepage at low voltages.

The following table shows the gains (ratios of deflection-to-input voltage) for the parallel and trapezoidal piezoelectric benders of same material, same thickness, and same length as determined during the tests.

Bender Shape	Type of Input Signal	Gain in./V
Parallel	Low freq ac	7.85×10^{-6}
Trapezoid	Low freq ac	10.7×10^{-6}
Trapezoid	dc	20×10^{-6}

Due to the considerable gain increase of trapezoidal bender shapes, priority in design will be given to those configurations which can be driven by trapezoidal benders.

<u>Further Hysteresis Tests:</u> Further tests were made to evaluate the hysteresis properties of piezoelectric benders. The items of interest were the influence of frequency and amplitude of the driving voltage on the hysteresis of the bender deflections, trapezoidal cantilever mounted benders as shown in Figure 5 were used and driven in the frequency range of 4 to above 100 Hz. Typical hysteresis plots copied from oscilloscope plots are shown in Figure 8 . Whereas a steady increase of hysteresis with frequency was expected, the opposite tendency - a decrease of the bender hysteresis with higher frequency - was observed at all amplitudes of the driving voltage. For instance at 140 V driving amplitudes hysteresis dropped from 38% of total

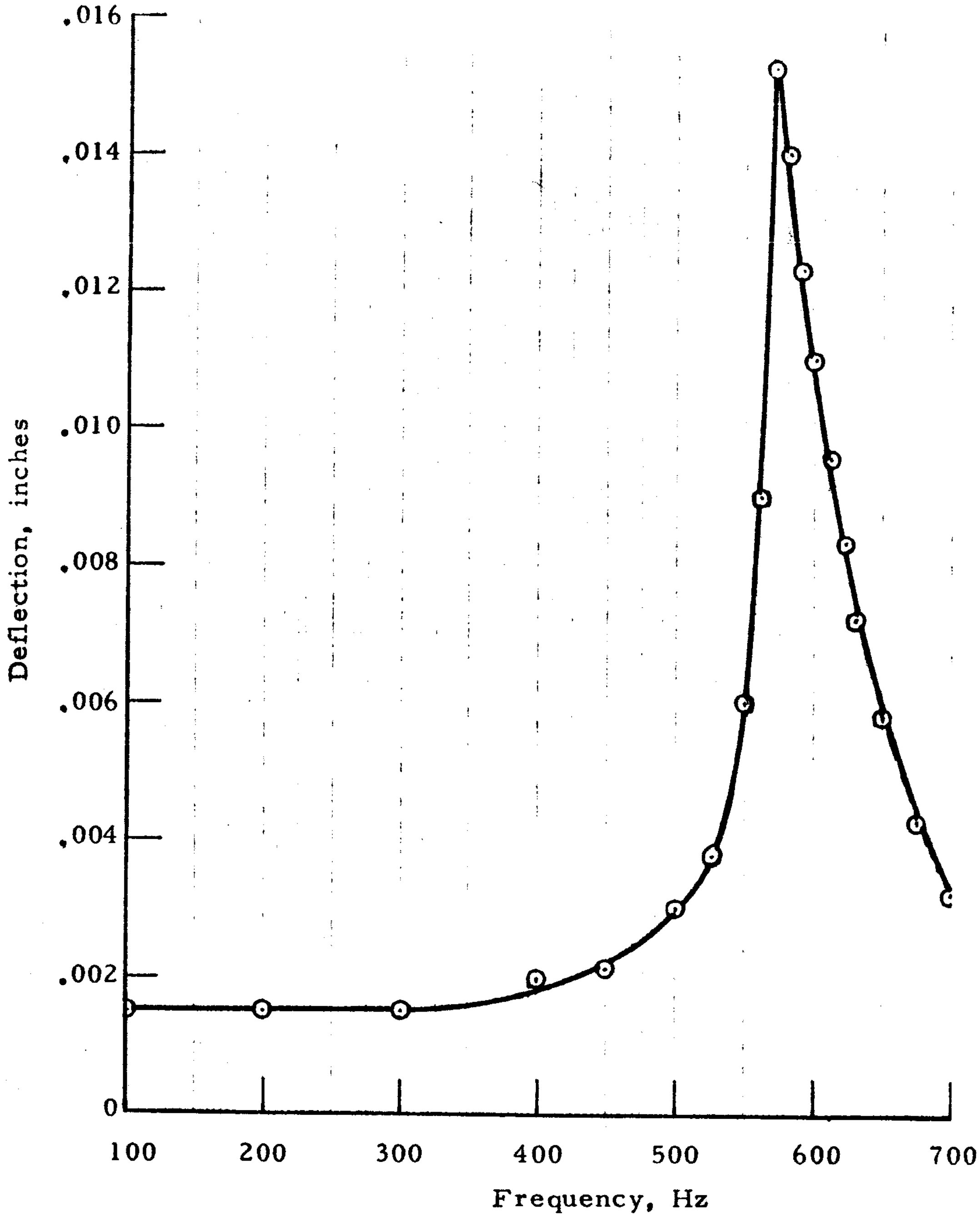


Figure 6 - Frequency Response of Trapezoidal Piezoelectric Bender with 140 V Peak Amplitude Driving Voltages

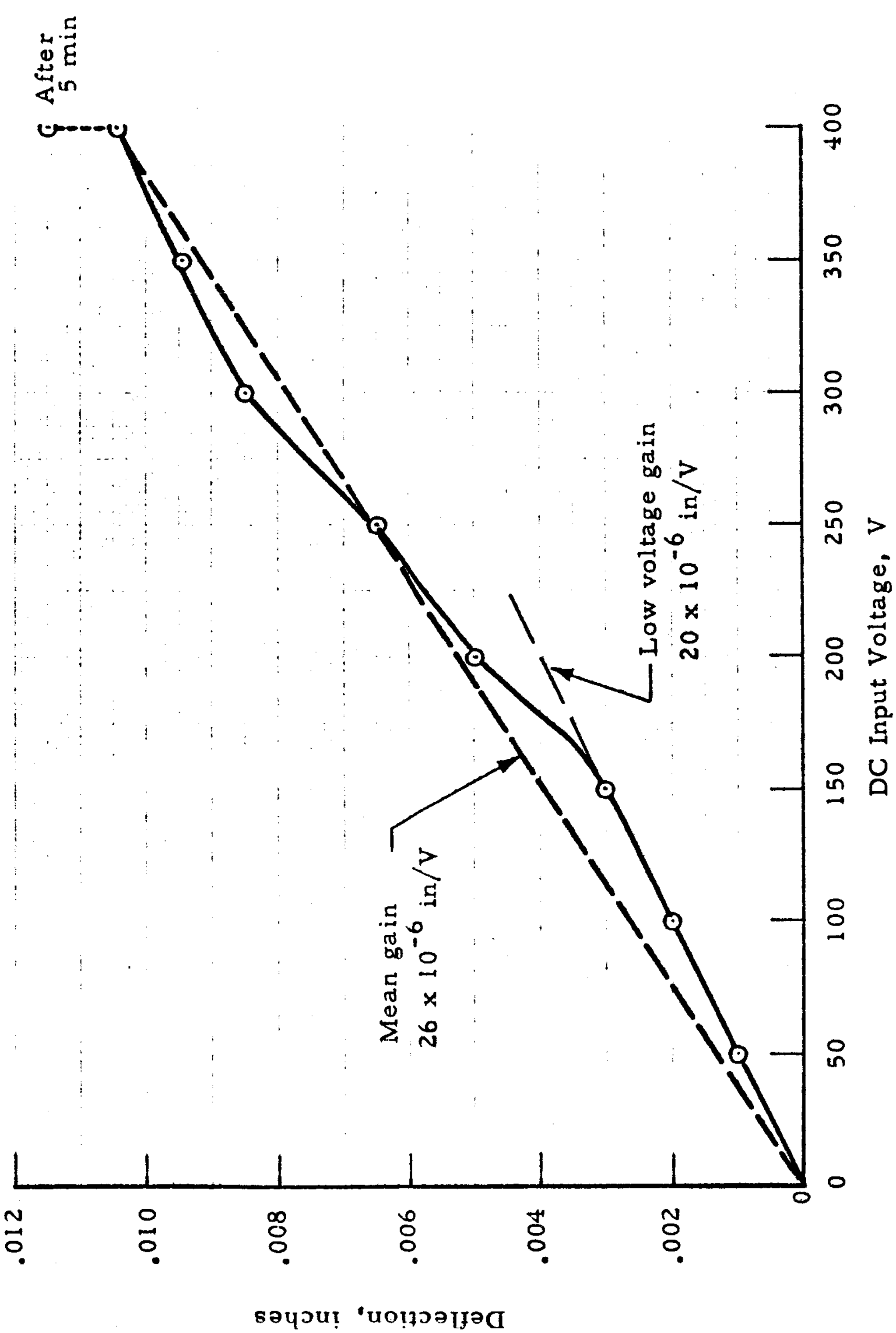
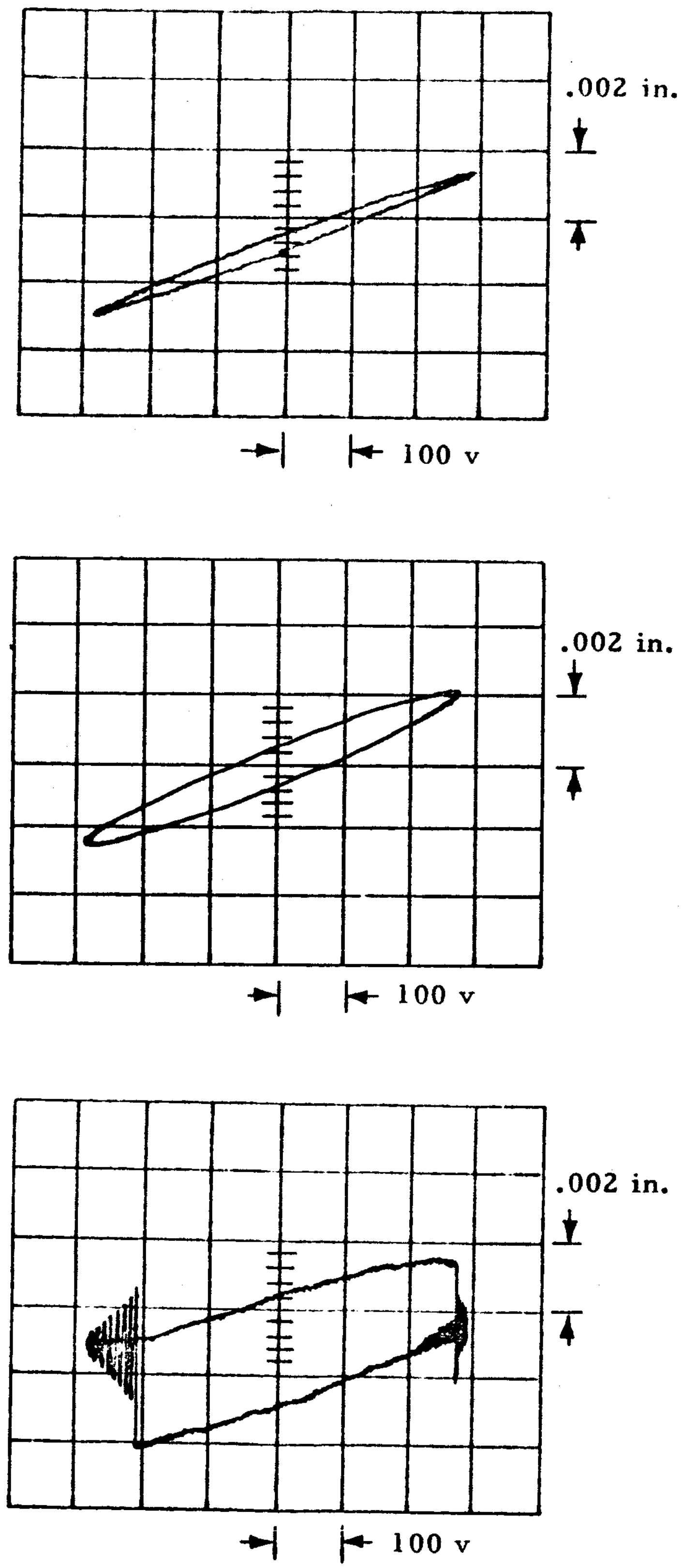


Figure 7 - DC Gain of Trapezoidal Piezoelectric Bender



(a) - 100 Hz 200 V rms
(560 P-P)

(b) - 7 Hz 200 V rms
(560 P-P)

(c) - 5 Hz 200 V rms
(560 P-P)

Figure 8 - Deflection vs Input Voltage of Piezoelectric Bimorph Benders 200 V RMS at Three Frequencies

deflection at 5 Hz to 0 at 100 Hz. At the highest amplitudes applied during the tests (280 V peak amplitude), these were 11% hysteresis at 100 Hz (Figure 8a), 22% at 7 Hz (Figure 8b) and a sudden change to discontinuous hysteresis patterns with two jumps in deflection near the peaks as shown in Figure 8c . This breakdown of piezoelectric force in the benders' active layers occurred though the driving voltage was well below the upper limit given by the manufacturer.

Further tests in the very low frequency and dc voltage range are being run with bender materials from different manufacturers to clarify this phenomenon observed.

If no better results are achieved during these further tests, a high frequency dither voltage must be added to the dc input voltage driving the benders.

Magnetic: Magnetic motivation may appear more attractive as the hardware develops, and especially with pulse duration modulation (see next section of report). However, unlike piezoelectrics, magnetic characteristics are well defined, so no basic studies are planned. Instead, work on magnetic motivation would progress when needed, beginning on a specific mechanical design.

Pulse Duration Modulation

Pulse Duration Modulation Electrofluid Converters: Pulse duration modulation can offer important advantage as an electrofluid conversion technique because drift and non-linearities such as hysteresis and temperature variations, do not affect the response. Neither does moderate variation of supply pressure affect response if the output is used to drive a digital element.

Four configurations are possible using PDM. Each case presented on page 14 uses progressively more of the functional blocks of Figure 9:

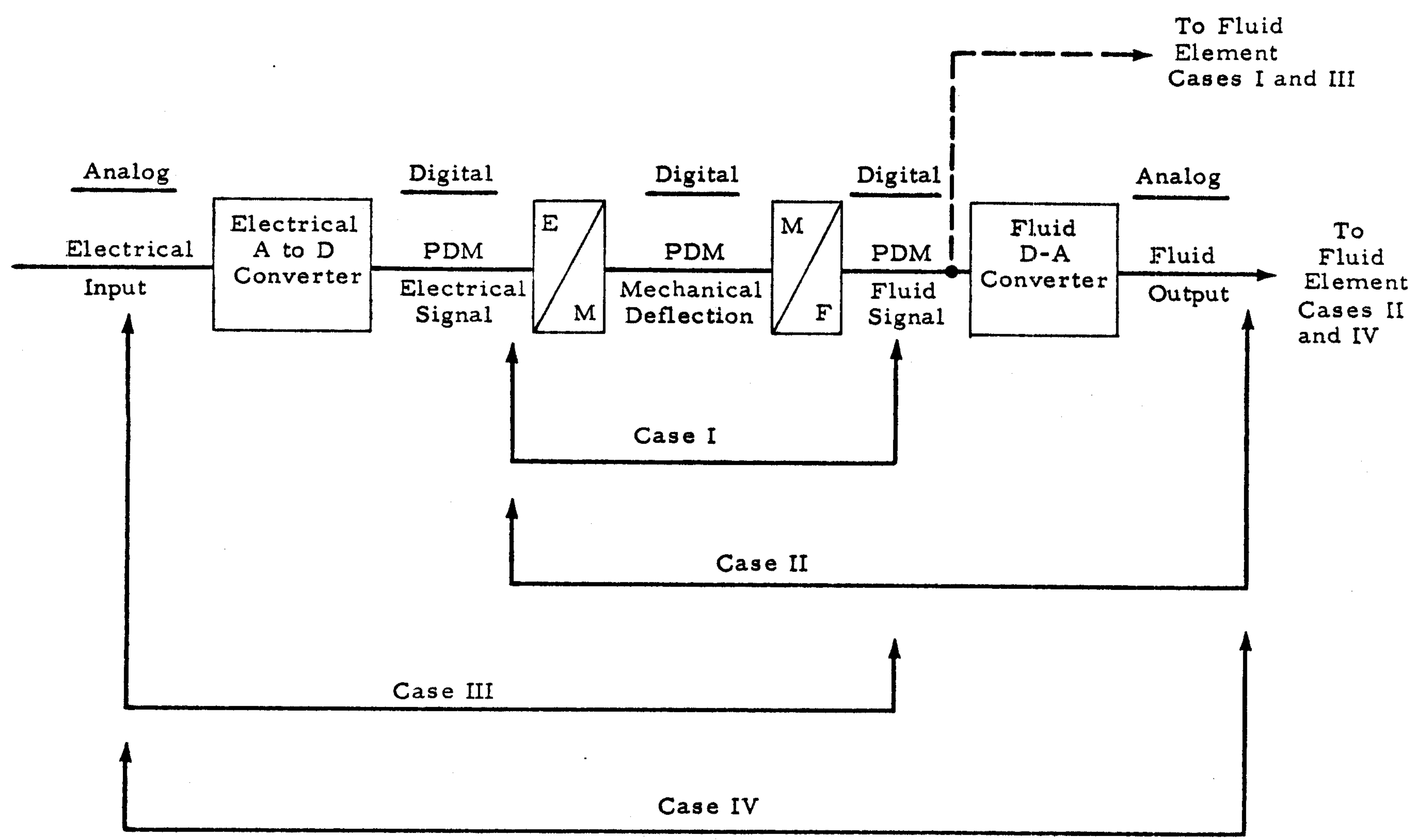


Figure 9 - Pulse Duration Modulation, Functional Diagram

Case	Electrical Input Signal	Fluid Output Signal
I	Digital (PDM Pulse Train)	Digital (PDM Pulse Train)
II	Digital (PDM Pulse Train)	Analog
III	Analog	Digital (PDM Pulse Train)
IV	Analog	Analog

It is assumed here that the proportional input signals of cases III and IV are converted to electrical PDM pulse trains by electrical circuits before they are fed into the electrofluid converter providing higher accuracy, faster response, and a smaller package than pure fluid A/D conversion. Hence, this investigation can be restricted to cases I and II with electrical bistable input signals.

Simple on-off fluid components can be used. For a basic feasibility study of the PDM technique a bistable wall attachment double-leg fluid amplifier was chosen, whose nozzle consists of two deflectable piezoelectric bimorphs (Figure 10). Also, magnetic motivation could be practical in the PDM arrangement. One application of magnetic motivation is shown in Figure 11.

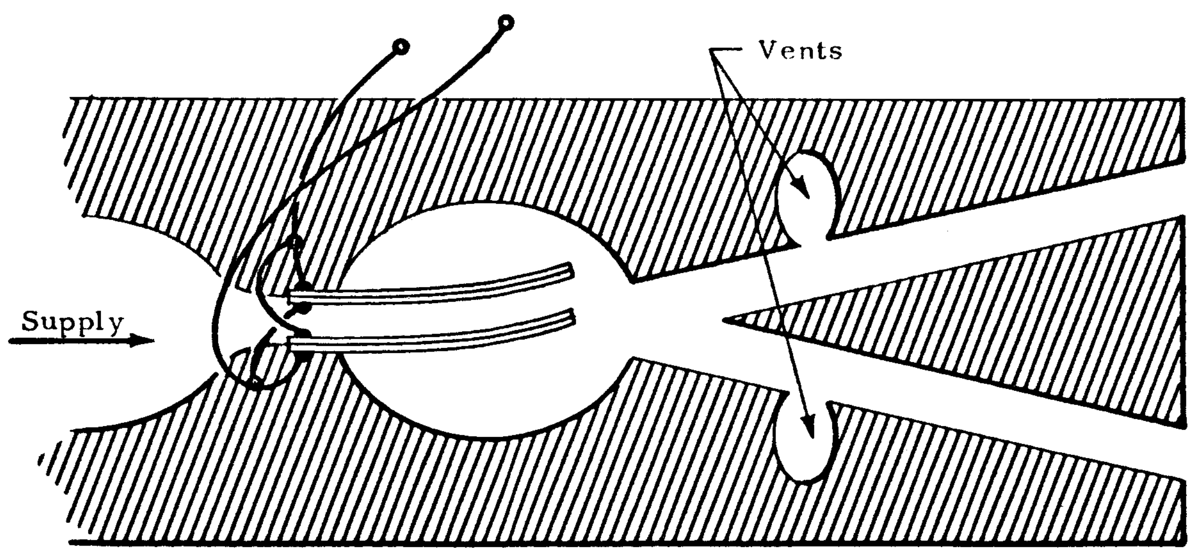


Figure 10 - Bistable Amplifier with Deflectable Piezolectrical Bender Nozzle

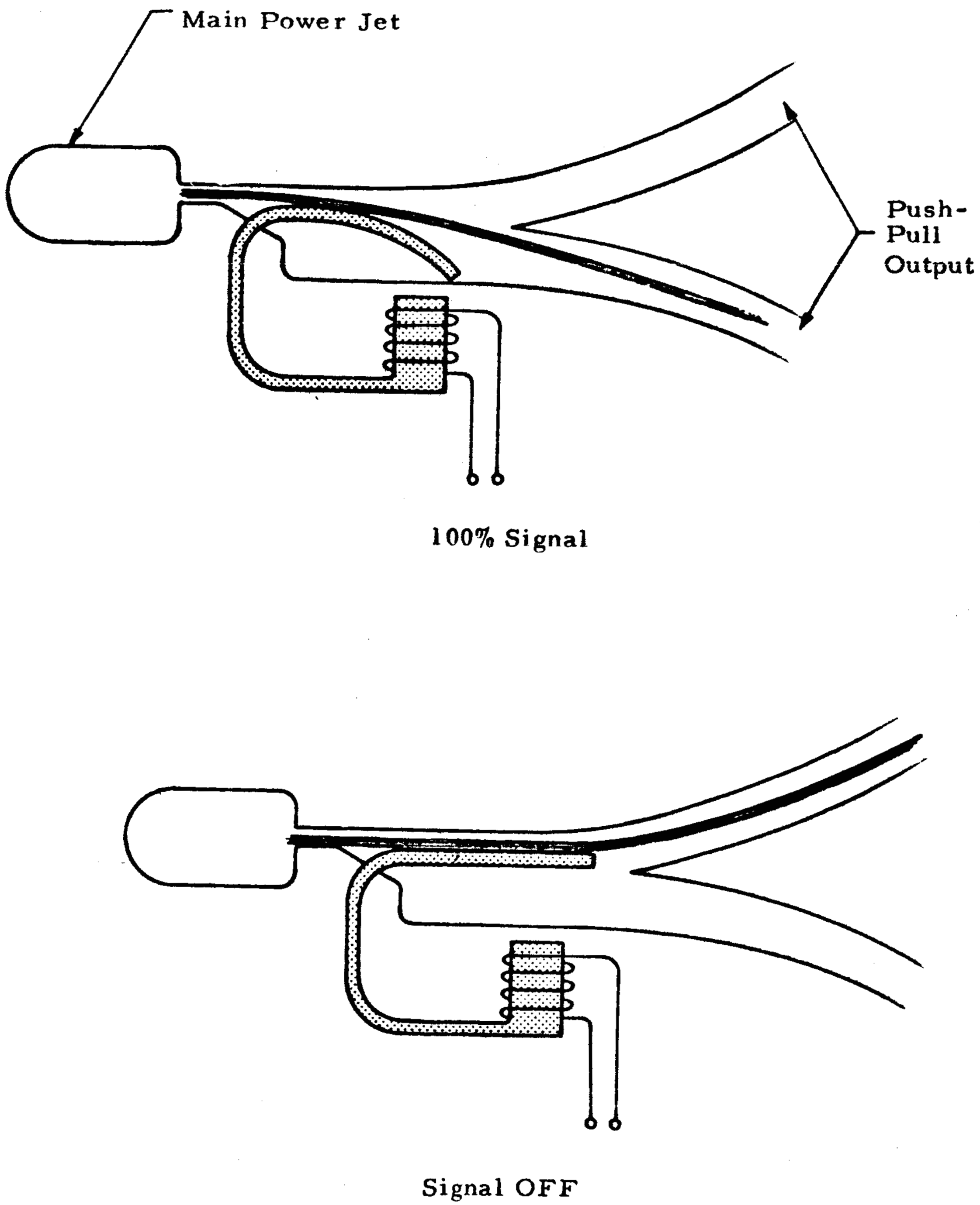


Figure 11 - Magnetic Motivation of Bistable Switching

Another bistable device, the turbulence amplifier, was not given further consideration because of its slow switching of 7 to 10 milliseconds compared with 1 millisecond or less for the double leg amplifier.

Whereas the converter of Figure 10 is sufficient in Case I, an additional conversion from PDM to proportional pressure signals is necessary in Case II.

One possible way for this conversion is shown in Figure 12 where a plenum is connected with each leg for time-averaging the output pressures. By appropriate plenum sizes and outlet orifices the difference, ΔP, of the plenum pressures is proportional to the electrical PDM input signal's dc component.

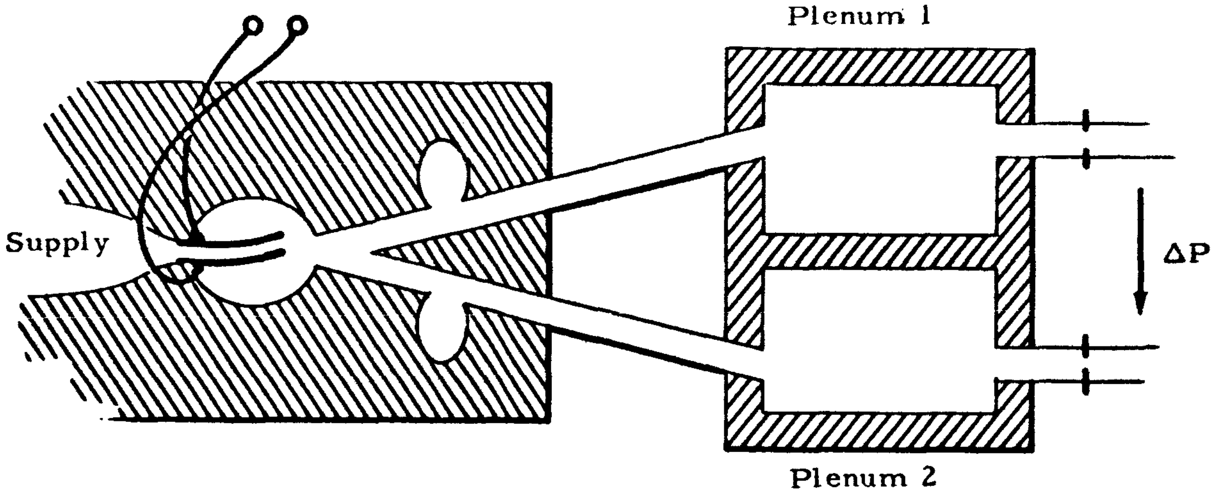


Figure 12 - Configuration for Time-Averaging Fluid PDM Signals

The PDM system of Figure 12 with adjustable plenum volume is being designed and fabricated using a movable nozzle to be built for proportional converters (see Reference 1, Figure 2). It will be tested upon completion. The switch times in the 1 millisecond range typical for bistable amplifiers indicate that high enough pulse rates are feasible.

System Design: Initial system design for a piezoelectric element with feedback has been started. The recently purchased pressure sensor for feedback has been operated using an oscillator-demodulator box already owned by HREC. The box is a Sanborn; some modifications were made and filtering was done to clear up the output signal.

Another matter may present some problem in instrumenting the system: The ± 300 V peak amplitude required to fully deflect piezoelectric benders must be supplied by an amplifier capable of responding from dc to 100 Hz. The best available amplifier on hand is an operational amplifier from the analog computer; it will drive satisfactorily ± 180 V. If oppositely poled benders are used, this may be all the voltage they require, so no other amplifier is being sought at this time.

FUTURE WORK

After tests with the manually movable nozzle test device, and some further tests with the piezoelectric pieces, a movable nozzle converter will be built with feedback.

Since indications are that creepage of piezoelectric materials is a greater percentage of deflection at low voltage than at high; tests of this will be made in the near future.

Although piezoelectric materials furnished by different suppliers are not expected to vary radically in performance, materials will be ordered from both U. S. Sonics and Gulton Industries for comparative purposes (material on hand is from Clevite only). From this broader sampling, the best material can be knowledgeably selected taking into account all material parameters, especially hysteresis. With the wider experience, special configurations and materials will probably be ordered, e.g., multiple laminations alternately poled for greater deflection from lower voltage.

One future study is to learn from existing literature the diffuser design which will provide minimum time delay without flow separation during pressure recovery. One particular article (Reference 2) will be ordered shortly.

REFERENCES

1. Floyd, G. O., Electrofluid Converter Study, August Progress Report, LMSC/HREC A712203, 10 September 1965.

2. Hackeschmidt, M., Design of Plane, Straight Diffusors of Small Length, Maschineubantechnik 13, 10, pp. 530-534, October 1965.