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Development of a Piezoelectric Dynamic Embosser for Use as a Reading Machine

by
G. J. Alonzo

March 1964

Technical Report No. 4813-4
Prepared under
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SOLID-STATE ELECTRONICS LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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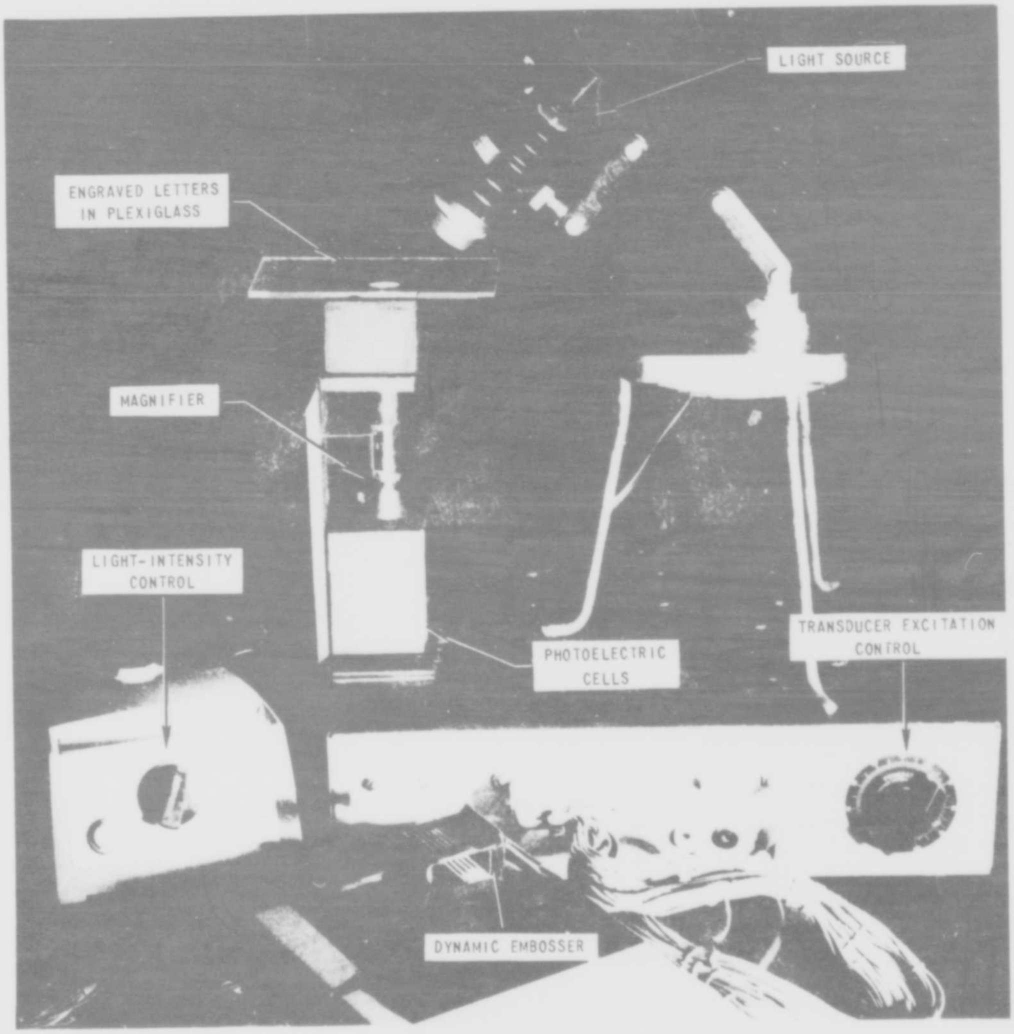

FRONTISPIECE. THE EXPERIMENTAL CHARACTER-SENSING PHOTOCELL PROBE--A DEVICE THAT USES A PHOTOCELL ARRAY MOUNTED TO DETECT TRANSMITTED LIGHT THROUGH LETTERS ENGRAVED IN PLEXIGLASS. This arrangement was used in the experiments to drive the embosser.

ABSTRACT

Attempts are in progress to increase the self-sufficiency of blind people by means of a device that will permit mechanical reading of printed material. In the detection of characters by tactile stimulation of the fingers, a new technique using a piezoelectric dynamic embosser is shown to be possible. The requirements imposed on the embosser in terms of the energy required by the finger and the energy available from the print-sensing probe are carefully examined. A piezoelectric transducer in a configuration known as a bimorph is found to satisfy the electromechanical conversion required without any amplifying network between the probe and transducer. The transducer is theoretically analyzed using a simple lumped model. From an equivalent circuit the properties of the transducer are easily determined. Experiments conducted on a bimorph verified the analytical results obtained. Properties of the finger, and other considerations necessary in the design of an embosser to enable the finger to detect characters, are examined. Results of tests using an experimental embosser are also presented.

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ACKNOWLEDGMENT

The author wishes to express his gratitude to Leo Parfaite of Stanford's Solid-State Electronics Laboratory and to Irwin Wunderman of hp Associates for their assistance in designing and building the photocells used. The support of hp Associates (an affiliate of the Hewlett-Packard Company of Palo Alto, Calif.) in making their facilities available is gratefully acknowledged. Appreciation is also expressed for the suggestions of Candy Linvill and Dr. John Linvill concerning the design of the embosser.

I. INTRODUCTION

Numerous attempts have been and are still being made to provide blind persons with a machine that will enable them to "read" from an ordinary printed page. These machines range from bulky and expensive units down to portable and relatively inexpensive devices. None of the portable machines have yet been entirely satisfactory. It is the purpose of this paper to show the definite feasibility of a portable machine using mechanical stimulation of the fingers by vibrating reeds to convey an image of a printed character to a blind person. In this machine the printed character is magnified and its image activates an array of photoelectric cells. The cells in turn activate an array of electromechanical reed transducers which provide the mechanical stimulation. The requirements which the embosser must fulfill are discussed first, followed by an analysis of a piezoelectric transducer and experimental verification of its terminal properties. Finally, the results of character-detection experiments are used to arrive at design considerations of a dynamic embosser. There is also a possibility that modifications to the reading machine will enable it to be used as a guidance device.

II. REQUIREMENTS OF THE EMBOSSER

A. METHOD OF EMBOSSING

Several possibilities exist for providing tactile stimulation by embossed reproduction. The embossing can be either dynamic or static and either solid or dotted. The four possibilities are illustrated in Fig. 1. In dynamic embossing, the raising of the shape of the letter is oscillatory, as opposed to static emobssing where the letter is raised once and remains until that letter is removed. In solid embossing the complete letter is raised, as opposed to dotted embossing in which an array of points representing the complete letter is raised. Selection of the method to be used depends primarily on the ease of detection by the finger.

To determine the most suitable type of embossing, numerous experiments were conducted using the different methods. In these experiments the letters were half an inch high. For the dotted technique the dot spacing and diameter were 0.085 in. and 0.030 in. respectively. When using the dynamic technique it was found that the easiest detection of characters occurs for a frequency of sinusoidal vibration of close to 60 cps.

Previous experiments have shown that solid statically embossed characters are easier to detect than those utilizing the dotted statically embossed technique. Experiments also show that the dotted dynamically embossed and solid statically embossed methods are about equal in ease of detection of characters; however, a little more practice is required when using the vibrating system. The use of larger dots decreased the ease of detection, indicating that the solid dynamically embossed technique would be inferior. Of the two superior methods--the solid static and dotted dynamic methods--the latter is easier to realize and therefore the required transducer properties for that system will be examined.

B. ENERGY DETECTABLE BY THE FINGER

The transducer must provide the proper mechanical vibration to stimulate the finger when it receives a signal from the print-sensing probe. The type of transducer needed will depend on the energy required

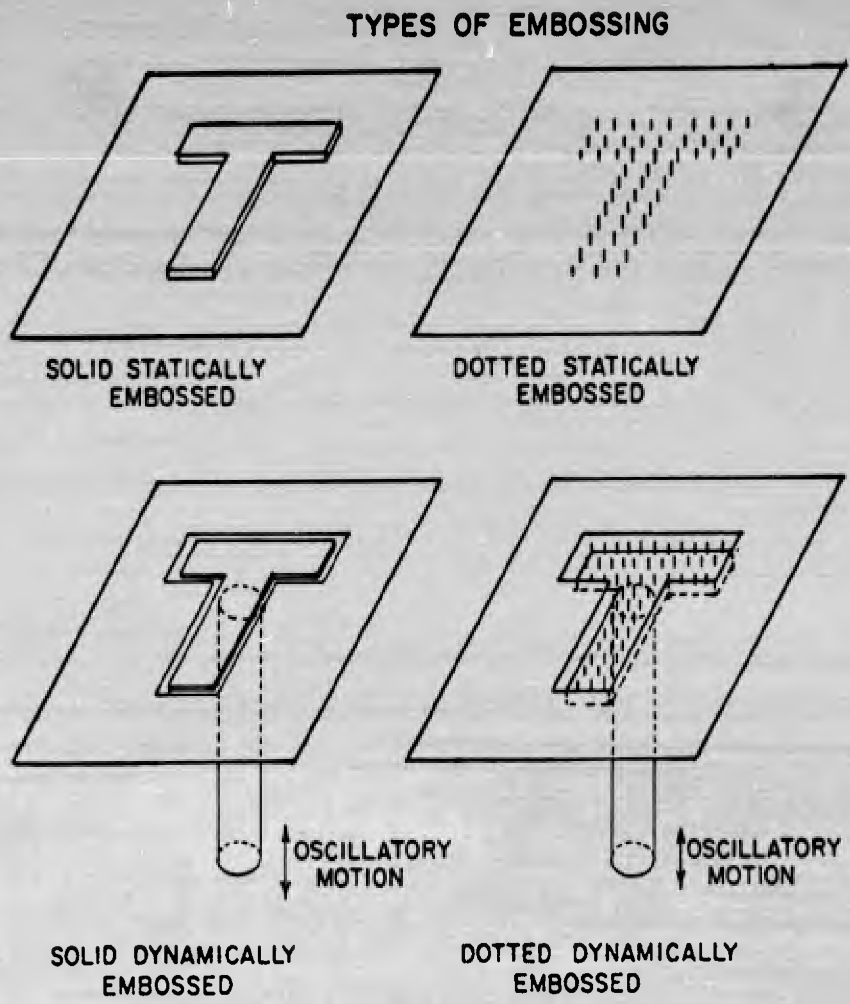


FIG. 1. TYPES OF EMBOSSING.

by the finger to detect the vibration and on the energy available from the probe.

Experiments on the finger provide the necessary information to determine the energy required for character detection. Using the end of a 0.030 in. wire as the stimulator, the following limits of finger sensitivity were found. In the dynamic mode the weakest detectable vibration at 60 cps occurred when the finger was in contact with a stimulator that developed a maximum force of 0.003 newton and a maximum displacement of 10^{-5} meters in an unloaded condition. In order to determine the energy required by the finger, the force and displacement resulting on the finger must first be determined. Knowing the force of the stimulator and its mechanical immittance of 0.003 meter/newton, one can calculate the force and displacement on the finger from its mechanical immittance. In the static condition the mechanical immittance of a finger was measured and found to be a compliance of 0.01 meter/newton. To determine the minimum energy detectable by the finger, the simple equivalent mechanical circuit shown in Fig. 2 will be used. The source is a 60-cps force generator of 0.003 newton peak and a constant force of 0.003 newton. The reason for the dc force is that it was felt the finger was in continuous contact with the wire stimulator and the finger can only experience a positive force in this situation. The frequency

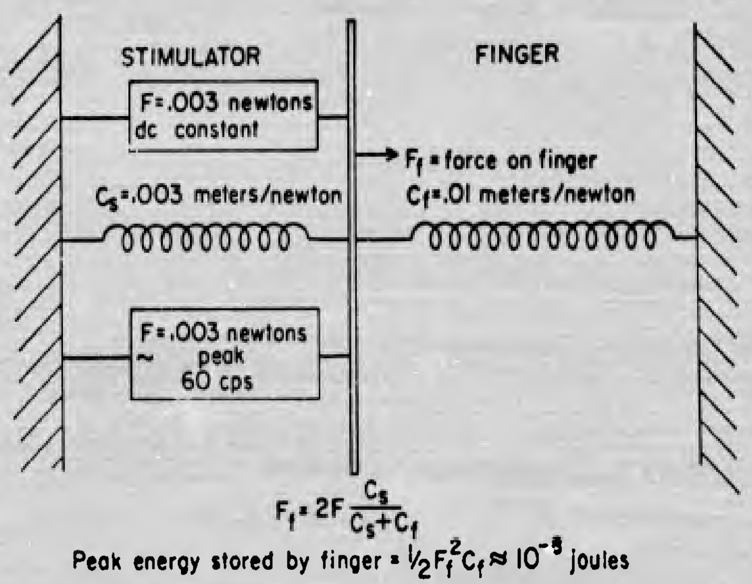


FIG. 2. EQUIVALENT CIRCUIT FOR MINIMUM VIBRATION DETECTABLE BY THE FINGER.

of 60 cps is well below the resonance of the stimulator, therefore its mass can be neglected and the source impedance is a simple compliance C_s = 0.003 meter/newton. The finger is also a compliance C_f = 0.01 meter/newton, and at this frequency the mass of the skin tissue moved and mechanical losses in the finger will also be neglected. Letting F_f be the maximum resulting force impressed on the finger, the peak energy transferred to and stored in the finger is

$$E_p = \frac{1}{2} C_f F_f^2 \tag{1}$$

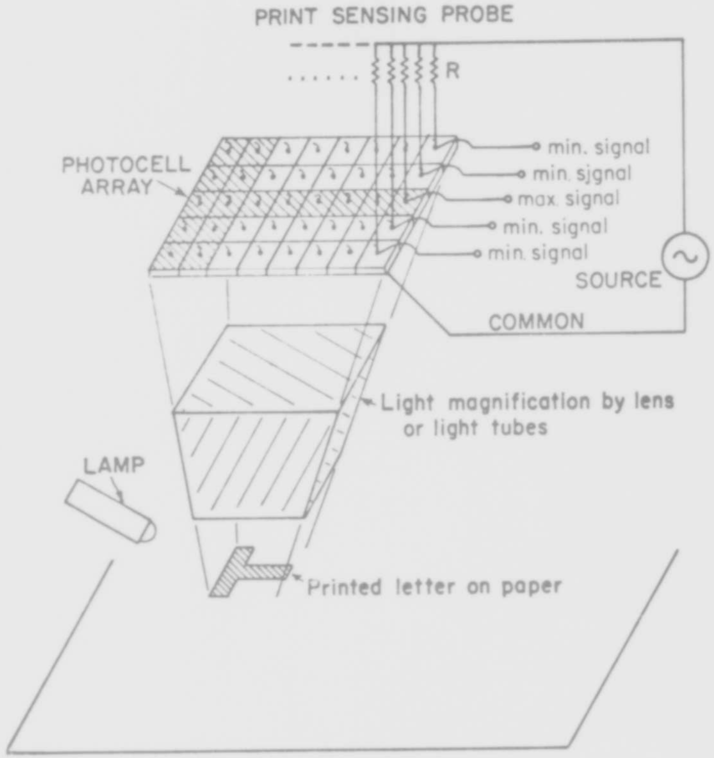
and, from the equivalent circuit,

$$E_p = \frac{1}{2} C_f \left(\frac{2FC_s}{C_s + C_f} \right)^2 = 10^{-8} \quad \text{joules minimum detectable energy} \tag{2}$$

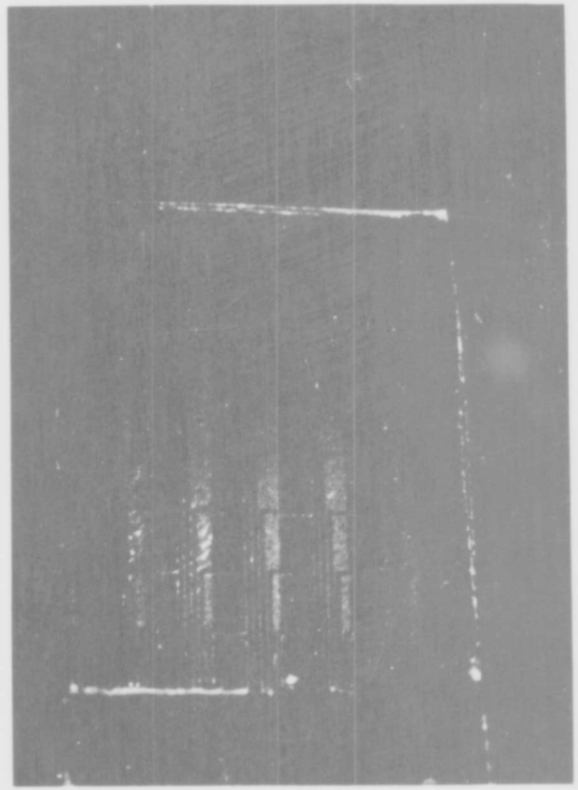
where F is the maximum force developed by the source. Increasing the force generator by 10 begins to induce uncomfortable sensations. Therefore, in order to provide fast, reliable detection the transducer should provide between 10^{-6} and 10^{-7} joules of reactive energy into a compliance of 0.01 meter/newton.

C. POWER AVAILABLE FROM THE PROBE

The print-sensing probe will now be examined to determine the characteristics of the signal to be received by the transducer. The probe is most conveniently an array of photocells. The cells should be positioned so that they are sensitized with reflected light from a printed page, as shown in Fig. 3a. Figure 3b shows a photocell array for detecting transmitted light through letters engraved in plexiglass. In order to provide maximum signals corresponding to the black portions of the letter, the photocells are used as shunt controllers. Typical impedance changes which can be anticipated in a photocell between the lighted and dark conditions are from 30 kilohms (kohm) to 1 megohm (meg) and therefore the source resistance R should be in the range of 1 meg. A signal level of 100 v can be controlled in the circuit shown and this results in an available signal power of about 0.01 w.



a. Schematic of print-sensing probe



b. Experimental photocell array

FIG. 3. PRINT-SENSING PROBE AND PHOTOCELL ARRAY.

D. REQUIRED TRANSDUCER EFFICIENCY

By knowing the available input signal power and the output energy required, the electromechanical conversion gain or efficiency can be determined. The finger receives energy during only half of the sinusoidal wave, and in half of a 60-cps wave the input is capable of delivering about 8×10^{-5} joules of real energy. Between 10^{-6} and 10^{-7} joules of reactive energy are required by the finger, but assuming that the stored energy is dissipated, electromechanical conversion efficiencies of only 1 percent will work.

Numerous electromechanical converters exist, but the requirements of this device practically eliminate all but one of them. Because not one but an array of transducers will be used, the physical size is important. Approximately 40 transducers must be positioned to stimulate one or several fingers. Magnetic transducers have the drawback that they are both bulky and of too low impedance. With electrostatic transducers the area is so small that the force developed is several orders of magnitude too low. However, a special configuration using a piezoelectric transducer meets all the requirements.

III. ANALYSIS OF THE TRANSDUCER

A. DESCRIPTION OF TRANSDUCER

Piezoelectric material experiences a strain (fractional change in length) under the influence of an electric field. Whether the strain is a contraction or expansion depends on the relative directions of the field and on the polarization in the material. The strain can be either parallel to the field, perpendicular to the field, or both. Magnitudes of strain available from piezoelectric materials are extremely small. Adequate deflection can be obtained by the use of a strip of two laminas, one of which expands while the other contracts, the bilaminar strip exhibiting flexure.

Piezoelectric material can be adapted to achieve flexure in a bilaminar strip since one side can be made to contract when the other side expands. A commercial device that obtains this flexure is called a bimorph and is shown in Fig. 4. The polarization is perpendicular to the length and in the same direction on both sides. Electrical connections made as shown in Fig. 5 result in a field parallel to the polarization and in opposite directions in the two sides. The strain perpendicular to the field is the component of interest since it results in one side contracting when the other side expands. Clevite Electronics Components of Cleveland, Ohio, manufactures a piezoelectric ceramic (PZT-5B) bimorph in the configuration of Fig. 4.

A suitable analysis of the transducer must provide results which correspond to the transducer's use in the embosser. It is desired to position numerous stimulators on the finger and a sufficient density of bimorphs is obtained using a cantilever-beam mounting. For the analysis an ideal mounting is assumed as shown in Fig. 5 where, with respect to the end of the bimorph, F is the force developed and s is the displacement. It will be shown that using a bimorph 0.024 in. thick, 1/16 in. wide and 1 in. long will produce a maximum displacement of 0.002 in. and a maximum force of 0.012 newton with the application of only 30 v.

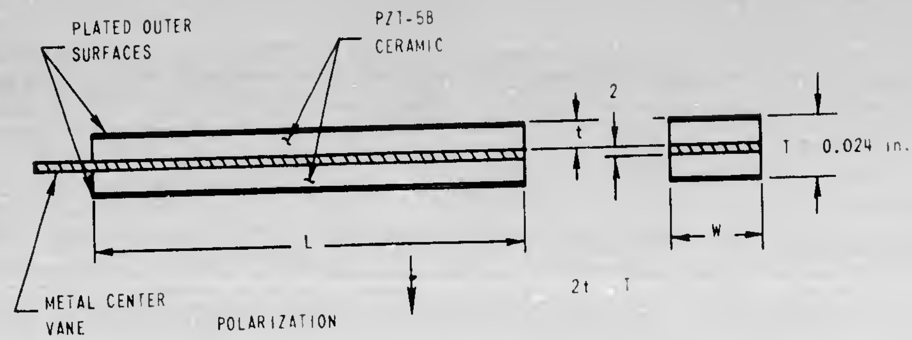


FIG. 4. ILLUSTRATION OF PIEZOELECTRIC BIMORPH.

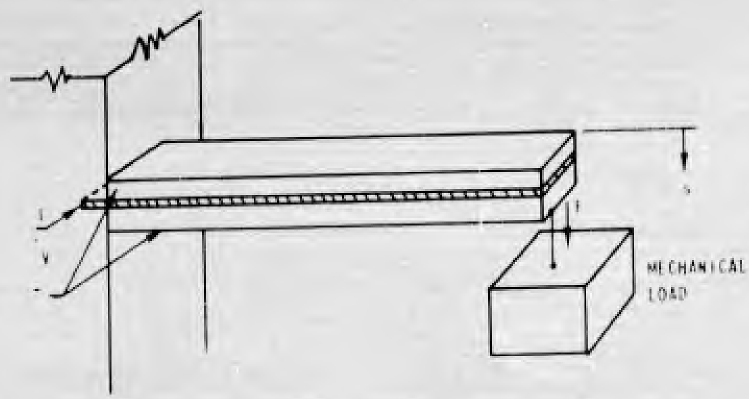


FIG. 5. CANTILEVER-BEAM MOUNTING OF BIMORPH SHOWING ELECTRICAL INPUT AND MECHANICAL OUTPUT.

The necessary physical constants of PZT-5B are:

$g_{31} = -9.1 \times 10^{-3}$ vm/n = piezoelectric modulus relating open-circuit field to applied stress (volt-meters/newton). Field perpendicular to strain.

$K = 2000$ = relative dielectric constant

$Y = 8 \times 10^{10}$ n/m^2 = Young's modulus--stress and strain parallel to each other (newtons/meter^2)

$\rho = 7.5 \times 10^3$ kg/m^3 = density (kilograms/meter^3)

B. LUMPED MODEL

1. Equivalent Circuit

An equivalent circuit* consisting of a simple lumped approximation of the birmorph can be obtained by examing it as a two-port device having an electrical input at port one and a mechanical output at port two. The influence of the mechanical load applied to the bimorph can be examined by using its equivalent lumped mechanical immittance. The bimorph and its load (Fig. 5) can be represented as in Fig. 6, where:

C_e electrical capacity of the bimorph
N electromechanical conversion coefficient of the transducer
C_m mechanical compliance of the bimorph
M equivalent mass of the bimorph
M_L mass of the load
C_L compliance of the load
R_L friction of the load
V_1 voltage applied to the bimorph
q_1 charge flow into the bimorph
s_2 mechanical displacement at the end of the bimorph and at the load
F_2 force acting on the bimorph resulting from the load
F_e an internally developed force in the bimorph

* Clevite Electronics Components, Bulletin No. 9231, Cleveland, Ohio, Apr 1958.

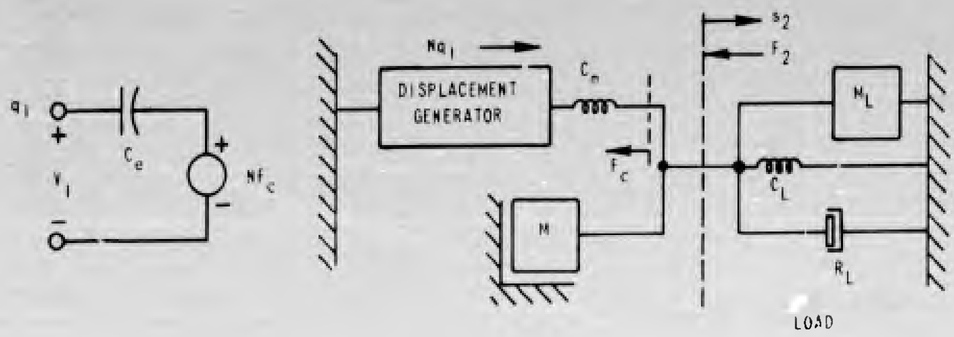


FIG. 6. EQUIVALENT CIRCUIT OF BIMORPH AND LOAD.

The differential equations describing this model are given below:

$$q_1 = (V_1 - NF_c)C_e \tag{3}$$

$$F_c = \frac{Nq_1 - s_2}{C_m} \tag{4}$$

$$F_2 = \frac{d^2 s_2}{dt^2} M_L + \frac{ds_2}{dt} R_L + \frac{s_2}{C_L} \tag{5}$$

$$F_2 = F_c - \frac{d^2 s_2}{dt^2} M \tag{6}$$

An analogous all-electrical model of the bimorph and its mechanical load can be easily derived using the analogies:

1 volt (v) = 1 newton (n)	1 ampere (i) = 1 meter/sec (m/sec)
1 coulomb (q) = 1 meter (m)	1 farad (f) = 1 meter/newton (m/n)
1 henry (h) = 1 kilogram (kg)	

Performing the necessary substitutions in Eqs. (3), (4), (5), and (6) yields:

$$q_1 = (V_1 - NV_c)C_e \tag{7}$$

$$V_c = \frac{Nq_1 - q_2}{C_m} \tag{8}$$

$$V_2 = \frac{d^2q_2}{dt^2} M_L + \frac{dq_2}{dt} R_L + \frac{q_2}{C_L} \tag{9}$$

$$V_2 = V_c - \frac{d^2q_2}{dt^2} M \tag{10}$$

where C_m and C_L are capacitances, M and M_L are inductances, and R_L is a resistance. An electrical circuit described by Eqs. (7), (8), (9), and (10) is given in Fig. 7.

In the application to be considered, the mechanical load is a small portion of the fingertip. By assuming that the frequency of operation is below the resonance of the system, the masses of the bimorph and load can be neglected. If the frictional losses of the finger are small, then its analogous resistance can also be neglected, thus yielding the simplified circuit of Fig. 8 and the following two-port equations:

$$V_1 = \frac{q_1}{C_c} + NV_2 \tag{11}$$

$$q_2 = q_1N - C_mV_2 \tag{12}$$

$$V_2 = \frac{q_2}{C_L} \tag{13}$$

The lumped constants shown in the analogous circuit of Fig. 7 are derived in the following analysis. Initially, the thickness of the centervane, as well as the electrode plating and the corrections accounting for the mechanical mounting of the bimorph, will be neglected for a first-order approximation.

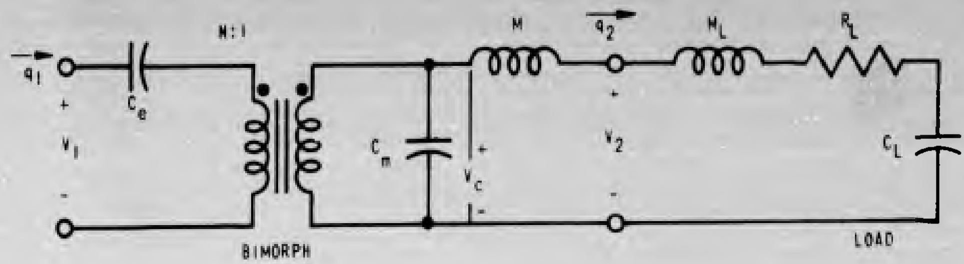


FIG. 7. ANALOGOUS CIRCUIT OF BIMORPH AND LOAD.

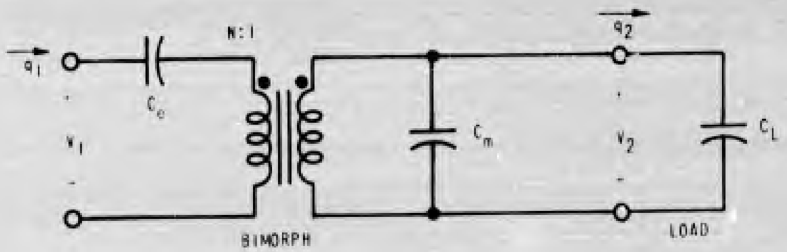


FIG. 8. SIMPLIFIED ANALOGOUS CIRCUIT OF BIMORPH AND LOAD.

2. Static Capacitance

The static capacitance is two parallel-plate capacitors in parallel.

$$C_e = \frac{\epsilon_o 2KLW}{t} \quad \text{farads} \qquad \epsilon_o = 8.85 \times 10^{-12} \text{ farads/meter} \qquad (14)$$

3. Compliance

The compliance will be calculated with use of Fig. 9. A displacement s at the end causes the bimorph to bend and the center forms an arc of radius r. Because of symmetry, there is no strain at the center, therefore

$$r\Phi = L \quad \text{meters} \qquad (15)$$

At a distance X from center, the change in length is

$$dL = \theta X \quad \text{meters} \qquad (16)$$

and the strain is

$$Sn = \frac{dL}{L} = \frac{X}{r} \qquad (17)$$

The strain can be related to the displacement by

$$s = (1 - \cos \theta)r \approx \frac{1}{2} r\theta^2 = \frac{1}{2} L^2 r \quad \text{meters} \qquad (18)$$

Substituting for r in Eq. (17) yields

$$Sn = \frac{2sX}{L^2} \qquad (19)$$

The stress in the length dimension at distance X from the center is

$$Ss = YSn = \frac{2YsX}{L^2} \quad \text{newtons/meter}^2 \qquad (20)$$

Consider a strip dX thick at distance X from center and with width W. The force in the length dimension is the area times the stress. Letting dl be the remental force in the length dimension and using Eq. (20)

yields

$$df = SsWdX = \frac{2YsWXdX}{L^2} \quad \text{newtons} \tag{21}$$

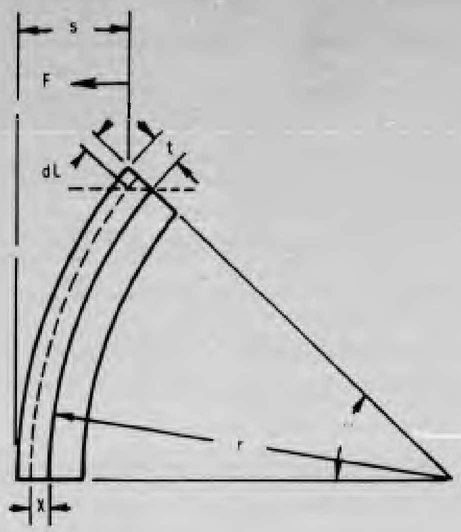


FIG. 9. ILLUSTRATION OF A BIMORPH UNDER STRAIN AND THE NOTATION USED TO ANALYZE ITS COMPLIANCE AND TURNS RATIO.

The center acts as a pivot, and the incremental force dF due to the longitudinal force df is

$$dF = \frac{Xdf}{L} = \frac{2sYWX^2dX}{L^3} \quad \text{newtons} \tag{22}$$

Integrating gives

$$F = \int_{-t}^{t} \frac{2YsWX^2dX}{L^3} = \frac{4YsWt^3}{3L^3} \quad \text{newtons} \tag{23}$$

and

$$C_m = \frac{s}{F} = \frac{3L^3}{4YWt^3} \quad \text{meters/newton} \tag{24}$$

4. The Effective Mass

To determine the effective mass M, it is seen from the equivalent circuit that a mass M concentrated at the end of the bimorph must store the same energy as the actual bimorph. This requirement assumes that the frequency is below the fundamental resonance, resulting in the simple mode of vibration in an arc. The mass of the bimorph is

$$m = \rho 2LWt \quad \text{kg} \tag{25}$$

Using Figs. 10a and 10b, assume the bimorph is vibrating with maximum displacement $s(\theta)$ at the end and that in the equilibrium position the end has velocity $v(\theta) = v$. The equilibrium velocity of any other point is proportional to the maximum displacement of that point. The mass of a slab of thickness $rd\varphi$ is

$$dm = \frac{m d\varphi}{\theta} \quad \text{kg} \tag{26}$$

The maximum displacement of mass dm at angle φ is

$$s(\varphi) = \frac{1}{2} \varphi^2 r \quad \text{meters} \tag{27}$$

and the equilibrium velocity of mass dm at angle φ is

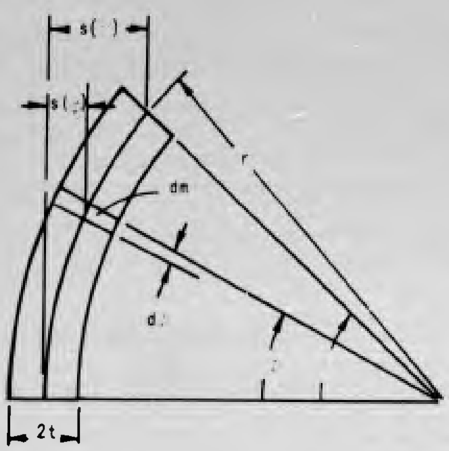
$$v(\varphi) = \frac{v\varphi^2}{\theta^2} \quad \text{meters/sec} \tag{28}$$

The stored energy of mass dm is

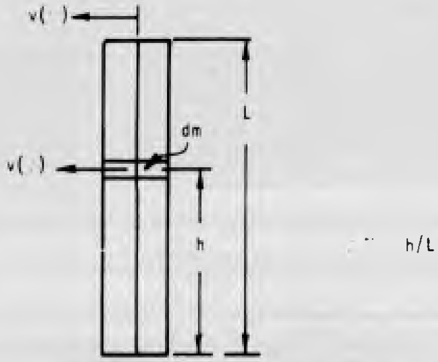
$$dE = \frac{1}{2} dm \left[v(\varphi)\right]^2 = \frac{mv^2 \varphi^4 d\varphi}{2\theta^5} \quad \text{joules} \tag{29}$$

and the total stored energy is

$$E = \frac{mv^2}{2\theta^5} \int_0^\theta \varphi^4 d\varphi = \frac{1}{2} mv^2 \left(\frac{1}{5}\right) \quad \text{joules} \tag{30}$$



a. Stressed position, maximum displacement



b. Equilibrium position, maximum velocity

c. Equilibrium position of equivalent mass M

FIG. 10. ILLUSTRATIONS OF NOTATION USED TO DETERMINE EFFECTIVE BIMORPH MASS.

If mass M were concentrated at the tip, as in Fig. 10c, then the total stored energy would be

$$E = \frac{1}{2} Mv^2 \quad \text{joules} \tag{31}$$

Equating energies yields

$$M = \left(\frac{1}{5}\right) m = \frac{2\rho LWt}{5} \quad \text{kg} \tag{32}$$

5. <u>Transducer Ratio</u>

The transducer ratio is easily derived from the stress relation of Eq. (20) used to calculate the compliance. Using Fig. 9, the stress is

$$Ss = \frac{2YsX}{L^2} \quad \text{newtons/meter}^2 \tag{33}$$

and solving Eq. (24) for s yields

$$s = C_m F = \frac{3L^3 F}{4YWt^3} \quad \text{meters} \tag{34}$$

Therefore, combining Eqs. (33) and (34) yields

$$Ss = \frac{3LFX}{2Wt^3} \quad \text{newtons/meter}^2 \tag{35}$$

The induced perpendicular field is

$$E(X) = g_{31} Ss = 3g_{31} \frac{FLX}{2Wt^3} \quad \text{volts/meter} \tag{36}$$

The open-circuit voltage is

$$V = \int_0^t E(X)dX = \frac{3g_{31}FL^3}{2Wt^3} \int_0^t XdX = \frac{3}{4} Fg_{31} \frac{L}{Wt} \quad \text{volts} \tag{37}$$

and the transducer ratio is

$$N = \frac{V}{F} = \frac{3}{4} g_{31} \frac{L}{Wt} \quad \text{volts/newton} \tag{38}$$

6. Lumped-Element Values

Following are the lumped-element values, for the parameters of PZT-5B, with all dimensions expressed in inches:

$$C_e = 9.0 \times 10^{-10} \frac{LW}{t} \quad \text{farads} \tag{39}$$

$$C_m = 3.7 \times 10^{-10} \frac{L^3}{Wt^3} \quad \text{meters/newton} \tag{40}$$

$$M = 4.9 \times 10^{-2} \, LWt \quad \text{kg} \tag{41}$$

$$N = 0.27 \frac{L}{Wt} \quad \text{volts/newton or meters/coulomb} \tag{42}$$

C. RESONANT FREQUENCIES

The analysis assumed a vibrating frequency well below the fundamental resonance of the device. Therefore, the fundamental resonant frequencies for two conditions will be calculated. The short-circuit resonant frequency calculated from the equivalent circuit is

$$f_s = \frac{1}{2\pi\sqrt{M(N^2C_e + C_m)}} = 34 \times 10^3 \frac{t}{L^2} \quad \text{cps} \tag{43}$$

The open circuit resonant frequency is

$$f_o = \frac{1}{2\pi\sqrt{MC_m}} = 37 \times 10^3 \frac{t}{L^2} \quad \text{cps} \tag{44}$$

D. TERMINAL PROPERTIES

The terminal properties of interest are the clamped and unclamped input impedance, the unclamped displacement sensitivity, and the clamped force sensitivity. The numbers given are for the dimensions measured in inches.

From the equivalent circuit the clamped input impedance is

$$Z_c = \frac{1}{j\omega}\left(\frac{1}{C_e} + \frac{N^2}{C_m}\right) \text{ ohms} \tag{45}$$

and the input is a capacitance of value,

$$C_c = \frac{C_e C_m}{C_m + N^2 C_e} = 760 \frac{LW}{t} \text{ pf} \tag{46}$$

The unclamped input impedance is

$$Z_u = j\left(\frac{N^2 \omega M}{1 - \omega^2 M C_m} - \frac{1}{\omega C_e}\right) \text{ ohms} \tag{47}$$

and the input is the static capacitance C_e for $\omega << 2\pi f_s$

$$C_u = C_e = 900 \frac{LW}{t} \text{ pf} \tag{48}$$

The unclamped displacement per volt is

$$\frac{s}{V} = \frac{NC_e}{1 - \omega^2 M(C_m + N^2 C_e)} \text{ meters/volt} \tag{49}$$

and, for $\omega << 2\pi f_s$,

$$\frac{s}{V} = NC_e = 2.4 \times 10^{-10} \frac{L^2}{t^2} \text{ meters/volt}$$

$$= 9.6 \times 10^{-9} \frac{L^2}{t^2} \text{ inches/volt} \tag{50}$$

The clamped force per volt is

$$\frac{F}{V} = \frac{NC_e}{C_m + N^2C_e} = 0.55\ \frac{Wt}{L} \qquad \text{newtons/volt} \tag{51}$$

To determine the sensitivities produced, some dimensions are assumed for the bimorph. For the bimorphs manufactured by Clevite, t = 0.012 in. Reasonable sizes for the width and length are 1/16 in. and 1 in. respectively. With these dimensions, the deflection sensitivity is found to be

$$\frac{s}{V} = 6.9 \times 10^{-5} \qquad \text{inches/volt} \tag{52}$$

The force sensitivity is

$$\frac{F}{V} = 4.1 \times 10^{-4} \qquad \text{newtons/volt} \tag{53}$$

The clamped and unclamped input impedance is the impedance of a 3900-pf capacitor and a 4600-pf capacitor respectively. At 60 cps this yields a magnitude of input impedance of about 500 kohm.

The signal amplitude required for detection by the finger can now be determined. From the previous experiments on the finger it was found that the minimum detectable excursion of the vibrating wire was 4×10^{-4} in. About 6 v, therefore, is the minimum detectable signal assuming the bimorph drives with enough force. Since the minimum detectable force was 3×10^{-3} newtons, a minimum of 7 v is required to provide adequate force. Therefore, using a bimorph of these dimensions, a minimum of 7 v can be sensed and about 40 v will provide fast, reliable detection.

Since the bimorphs will tolerate about 200 v before depolarization begins, and the print-sensing probe can control around 100 v, one can see that even with its low conversion efficiency the bimorph will work. The simple control circuit required is shown in Fig. 11 where R is about 500 kohm.

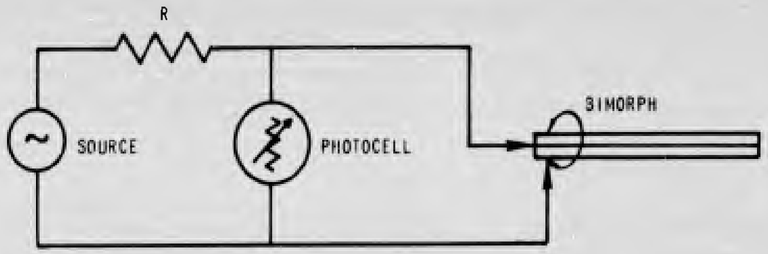


FIG. 11. BIMORPH CONTROL CIRCUIT.

IV. EXPERIMENTAL VERIFICATION OF THE TERMINAL PROPERTIES OF A BIMORPH

A. EFFECTS OF CENTERVANE AND UNSTRESSED MOUNTED END

In order to experimentally verify the calculated results, the contributions of the centervane and unstressed mounted end as illustrated in Fig. 12 will be included. First, consider the influence of the centervane. It is still assumed that the density and Young's modulus of the centervane are the same as the ceramic. Therefore, C_m and M are unaltered. The static capacitance becomes

$$C_e = \frac{\epsilon_o 2KLW}{t-\delta} = \frac{\epsilon_o 2KLW}{t}\left[\frac{1}{1-(\delta/t)}\right] \text{ farads} \qquad (54)$$

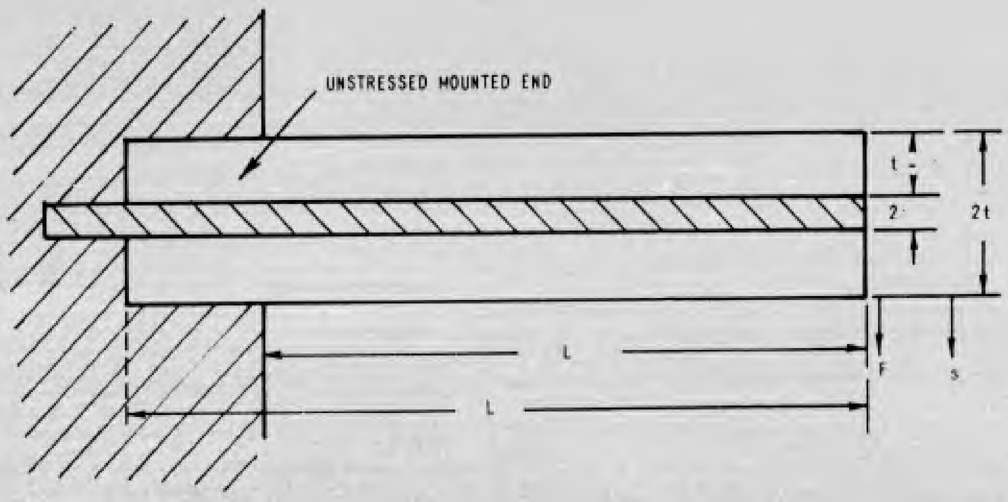


FIG. 12. INCLUSION OF CENTERVANE THICKNESS AND UNSTRESSED MOUNTED END.

The transducer ratio is also altered since the integral in Eq. (37) is only integrated from $X = \delta$ to $X = t$, resulting in

$$N = \frac{3g_{31}L}{4Wt^3}\left(t^2 - \delta^2\right) = \frac{3g_{31}L}{4Wt}\left(1 - \frac{\delta^2}{t^2}\right) \quad \text{volts/meter} \qquad (55)$$

If, as a result of mounting, $(1 - \beta)$ of the length is unstressed at the mount, then the effective mass and compliance are corrected by replacing L with βL. The capacitance C_e is also reduced by β since no charge is displaced in the unstressed segment of the length. The unstressed portion also acts as a capacitive load and reduces the induced emf by β at the terminals. The induced emf in the stressed portion is found by replacing L with βL and results in a transducer ratio of

$$N = \frac{3g_{31}L}{4Wt}\left(1 - \frac{\delta^2}{t^2}\right)\beta^2 \quad \text{volts/newton} \qquad (56)$$

Also

$$C_e = \frac{\epsilon_o 2K\beta LW}{t}\left[\frac{1}{1 - (\delta/t)}\right] \quad \text{farads} \qquad (57)$$

$$C_m = \frac{3\beta^3 L^3}{4YWt^3} \quad \text{meters/newton} \qquad (58)$$

and

$$M = \frac{2}{5}\rho\beta LWt \quad \text{kg} \qquad (59)$$

Some bimorphs 1 in. long by 1/16 in. wide by 0.024 in. thick were purchased from Clevite. The centervane thickness was measured at 0.006 in. One of the bimorphs was mounted as shown in Fig. 13 to determine its properties experimentally. The calculated lumped constants of the equivalent circuit using $\beta = 0.8$ and $\delta = 0.003$ in. are:

$C_e = 4900$ pf

$C_m = 0.0018$ meters/newton

$$M = 2.9 \times 10^{-5} \quad kg$$

$$N = 220 \quad volts/newton \quad or \quad meters/coulomb$$

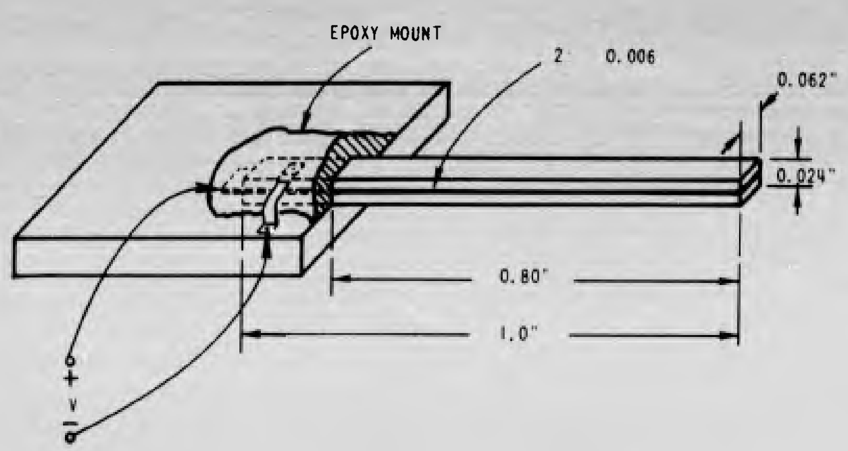


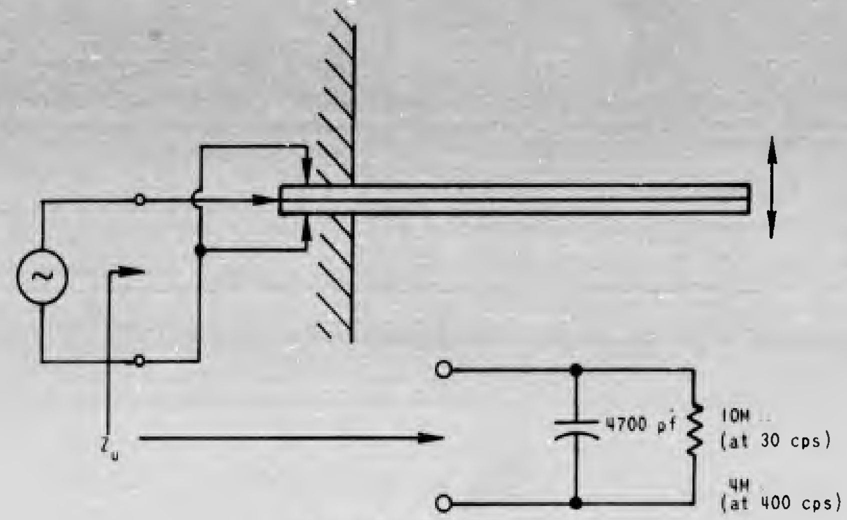
FIG. 13. PHYSICAL SIZE AND MOUNTING OF THE BIMORPHS USED IN THE EXPERIMENTS.

B. EXPERIMENTAL MEASUREMENTS

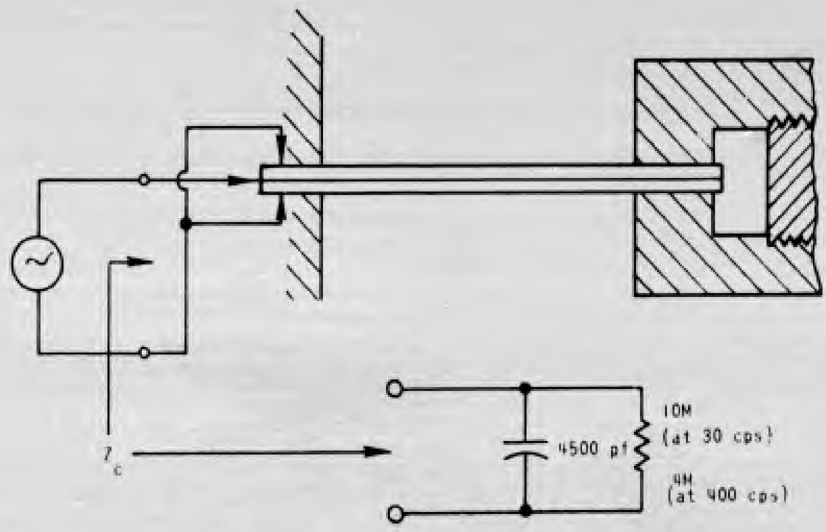
The input capacitance was measured using a Wayne Kerr Universal bridge at various frequencies between 30 cps and 400 cps for both the clamped and unclamped conditions and is illustrated in Fig. 14. The clamped and unclamped capacitances remained constant at 4500 pf and 4700 pf respectively over the above frequency range. It was also noticed that the effective loss in parallel with the capacitance decreased from 10 to 4 megohms as the frequency increased from 30 cps to 400 cps for both constraints on the bimorph.

The calculated capacitances are 4400 pf for the clamped condition and 4900 pf for the unclamped constraint. Agreement to within 6 percent is quite acceptable because the thickness of the epoxy layer bonding the ceramic to the metal vane was small but not negligible.

The deflection sensitivity was measured by mounting the bimorph under a ten-power microscope. A movable calibrated hairline in the



UNCLAMPED INPUT IMPEDANCE



CLAMPED INPUT IMPEDANCE

FIG. 14. INPUT CHARACTERISTICS OF THE BIMORPH.

eyepiece allowed accurate measurements of the deflection. With this elaborate test rig, it was determined that the deflection experienced hysteresis. The hysteresis loop measured is shown in Fig. 15. The deflection proceeds along the hysteresis loop in a counterclockwise direction. The measured deflection sensitivity is taken as the average slope of Fig. 15 and is 3.7×10^{-5} in./v. The calculated sensitivity is 4.2×10^{-5} in./v. These results agree within 12 percent. Since C_e was 6 percent in error, the measured N is also only 6 percent different from the calculated value.

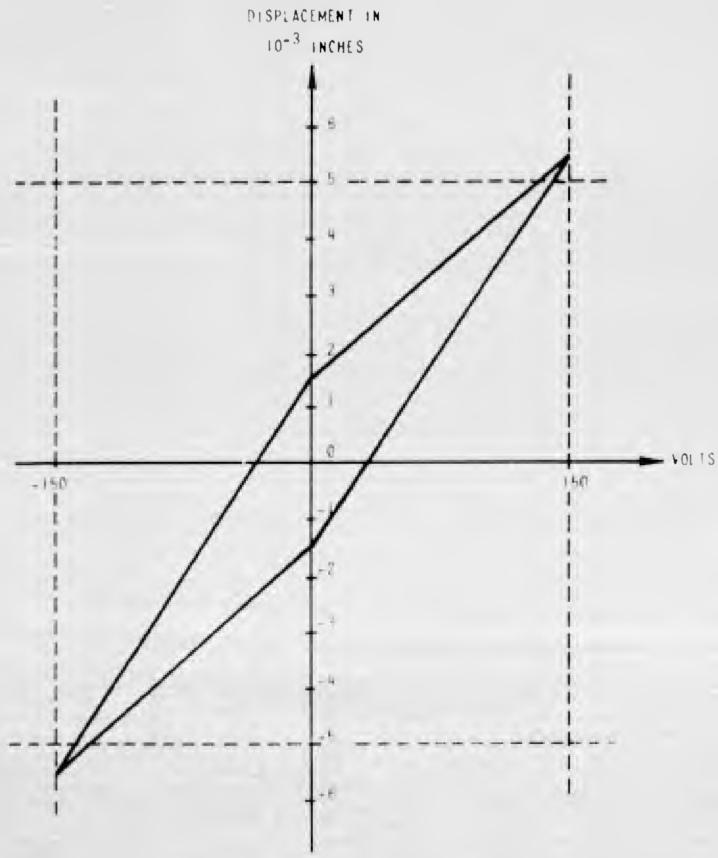


FIG. 15. MEASURED DISPLACEMENT VS APPLIED VOLTAGE.

Measurement of the force sensitivity was the most difficult, and the result was felt to be valid only to ±20 percent. The problem arises in trying to measure forces of 0.01 newton and still maintain the end of the bimorph at the original position. Hysteresis effects were again present but the complete loop was not determined. A triple beam balance was actuated by the end of the bimorph. After application of 150 v the scale was readjusted, and the change in mass required to return the bimorph to its original position is the desired equivalent force. The mean of 15 measurements was 5.5 grams for 150 v or a force sensitivity of 3.6×10^{-4} n/v. The calculated sensitivity is 5.4×10^{-4} n/v. There is a discrepancy of one-third of the calculated value in this measurement and it is probably the combined results of hysteresis and poor measurement technique.

Determination of the resonant frequency was made using a 600-ohm source and resonance was detected at 630 cps by noting a peak in the mechanical vibration. The calculated resonance is $f_s = 660$ cps.

With the exception of the force sensitivity, close agreement is found between the theoretical and measured properties of the bimorph.

V. DESIGN CONSIDERATIONS OF THE DYNAMIC EMBOSSER

A. PROPERTIES OF THE FINGER

There are several properties of the finger that influence its ability to detect dotted, dynamically embossed characters. Considerable information is required to recognize characters and the amount of information that can be transferred simultaneously by means of the finger is ultimately limited by the nerve density at the area of the finger being stimulated. However, before this ultimate density of information can be approached, the following two important factors must be optimized:

1. The learning process involved in teaching the finger to detect dotted dynamically embossed characters, and
2. localizing the area of stimulation of individual stimulators

1. Optimum Density of Stimulators

The optimum density depends on the sensitivity, inherent and developed, of the finger. With practice, the density and amount of information detectable increased and the ability to recognize characters improved considerably. The finger must be taught to decipher more information than is normally required, because in normal use there is little demand for differentiating between simultaneous signals at different locations on the finger. This learning process is very important since presenting more information than can be deciphered results in increased confusion and decreased ease of character detection. Therefore, the optimum density of the vibrating bimorphs is dependent on the ability of the finger to distinguish between individual stimulators.

2. Localizing the Signal

The transmission of the signal from the point of stimulation to other locations on the finger must be reduced to a minimum. The factors that influence this undesirable effect are:

1. The frequency and waveform of the vibration of the stimulators,
2. The direction of motion of the stimulators relative to the finger,
3. The area of contact between the stimulator and the finger,

4. Vibration transmission between adjacent stimulators,
5. Occurrence numbness in the finger, and
6. Amplitude of the vibrating stimulation.

Both the fundamental frequency and the waveshape of vibration of the stimulation greatly influence the localization of the signal. It was experimentally found that transients and fast motions as found in square pulses and sawtooth waveforms were not desirable for detecting characters. Even for sinusoidal vibration, as the frequency increased above 120 cps there was a noticeable increase in the transmission of the stimulation to surrounding areas. The sensitivity of the finger increased with higher frequencies, but character detection was impaired even with reduced amplitude of vibration. As the frequency was reduced below 30 cps, the stimulation felt increasingly discontinuous and detection of characters became difficult. A 60-cps sinusoidal vibration was found to be close to an optimum stimulation.

The direction of the vibrating stimulator relative to the finger was found to strongly influence its ability to detect characters. An illustration of the relative directions of stimulation is shown in Fig. 16. With a single vibrating reed there was only a slight

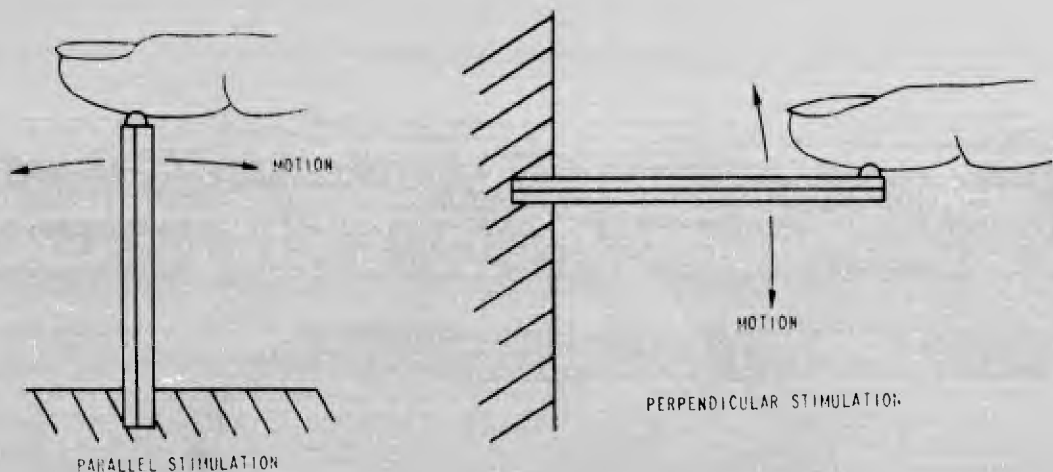


FIG. 16. DIRECTION OF STIMULATION.

improvement in detection with the motion perpendicular rather than parallel to the skin, but when several reeds are used the ability to determine which reeds are vibrating and which are not is greatly enhanced with perpendicular motion. This ability to detect a pattern is only slightly reduced when the motion is at 45 deg. It is believed that the magnitude of the perpendicular component is important, not the absence of a parallel component of motion, probably due to the excitation responses of the nerves to perpendicular and parallel motion of the skin.

Reducing the contact area between the finger and the stimulator helps to minimize the transmission of signals to other locations on that finger. However, the end of the stimulator should be smooth and of large enough area so that the finger can be moved across the stimulator without restriction.

The use of a base plate as illustrated in Fig. 17 greatly increases the attenuation of vibration transmission between stimulators. The base plate has a hole for the end of each reed, and in the unexcited condition the top of the plate is positioned to be level or slightly above the ends of the stimulators. The hole should be as small as possible and still allow room for the reeds to vibrate. A further benefit from the base plate results because the finger is no longer in

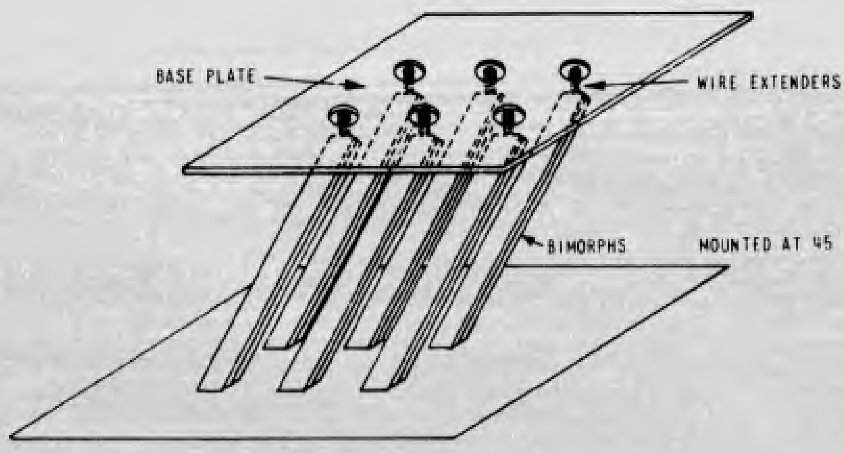


FIG. 17. ILLUSTRATIVE MODEL OF DYNAMIC EMBOSSER.

constant contact with the stimulators. Without the base plate the finger has to differentiate between the vibrating and static modes of stimulation, but with the base plate it only needs to detect the difference between essentially no stimulation and the vibrating stimulation. Such a marked improvement in character detection resulted from using the base plate that its use is deemed essential.

It was found that continuous stimulation of the finger produces a numbing effect which renders the finger useless for detecting characters. The problem is almost eliminated by use of the base plate described above since the finger is no longer continually in contact with the small ends of all the stimulators. The numbing effect can still occur, however, and is accelerated with vibrating stimulation. It is therefore desirable to keep the amplitude of vibration as low as possible.

The amplitude of vibration influences the ease of detecting a signal, the magnitude of unwanted stray stimulation, and the speed with which numbness occurs. To minimize these last two effects, it is desirable to keep the vibration amplitude as small as possible. It was found that the same ease of character detection could be attained, using less dynamic stimulation, when a static deflection was simultaneously applied using a dc voltage in series with the sinusoidal source.

B. DESCRIPTION OF ARRAY

Further considerations in the design of the dynamic embosser are physical size of the array and the number of elements in it. The experimental array provided the information needed to predict a more optimized embosser design. The photograph of the experimental embosser shown in Fig. 18 provides a closeup of the eight-row, five-column array. The reeds described previously (see Fig. 13) were mounted at 45 deg. A base plate was used and small wires were fixed to the ends of the bimorphs to reduce the contact area and extend them even with the base plate. A center-to-center spacing of 3/32 in. in a plane parallel to the base plate was used.

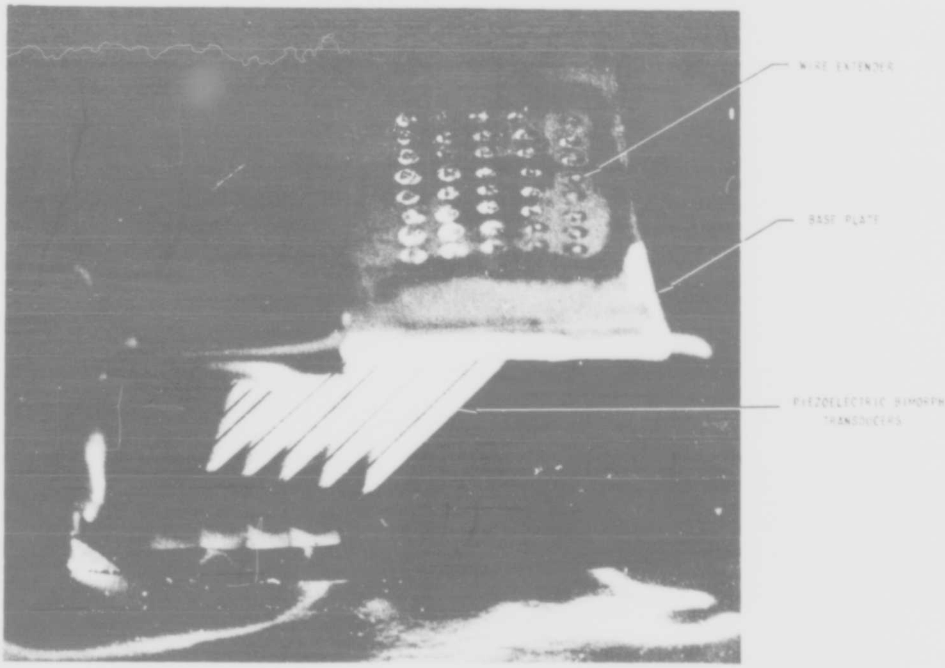


FIG. 18. PHOTOGRAPH OF THE EXPERIMENTAL EMBOSSER.

The number of reeds in the array must be enough to allow detection of all necessary characters but not so many that the finger becomes confused and unable to distinguish individual stimulators. The amount of information required depends on the manner of presenting a character. Experiments show that when the vibrating character is stationary, it is almost impossible to detect it. However, if one is allowed to move the character across the array as in Fig. 19, then detection is much simpler. When scanning a character in this manner, only one column of stimulators is essential since a person is capable of connecting the information and forming a complete image of the character. The work of John S. Abma* shows that segmenting the vertical dimension into a

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*E. Bennett, J. Degan, and J. Spiegel, Human Factors in Technology, McGraw-Hill Book Co., New York, 1963, Chapter 19.

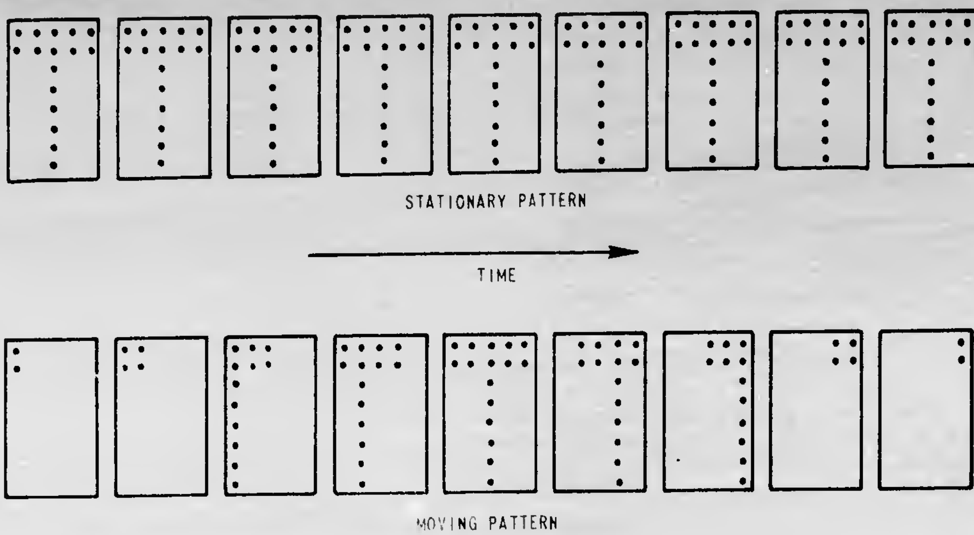

FIG. 19. METHODS OF CHARACTER PRESENTATION. Dots represent a vibrating stimulator in the array.

minimum of eight sections is adequate for recognizing printed material, but that it is necessary to be able to distinguish any combination of those segments. Although increasing the number of segments makes vertical positioning less critical, and using more than one column of reeds provides redundant information--thus allowing quicker detection of characters--it should be emphasized that the absence of confusion between stimulators must still be maintained. Experiments indicate that although the use of a single column is less confusing initially, with practice the subject prefers more information.

Experiments using the dynamic embosser indicated that the 3/32-in. spacing of stimulators is too close: the finger is unable to distinguish individual stimulators. Also, using only capital letters proportioned so that the complete letter could be covered by the 8 x 5 array, the finger was unable to detect most letters. Expanding the letters in the width dimension so that only half of the letter was sensed at one time resulted in greatly improved detection, but the finger still did not provide enough definition using the 3/32-in. stimulator spacing. Using a 3/16-in. spacing of four stimulators, the finger was able to detect which of the possible combinations was being stimulated. It is concluded from these experiments that a physically larger array is necessary.

C. DESIGN RECOMMENDATIONS

The following recommendations should considerably improve the reliable detection of all characters using a dynamic embosser. By positioning the stimulators under two or three joints of the first three fingers the necessary distinguishability of stimulators should be attained. Because the fingertips are the most sensitive region, the stimulators should be arranged so that the first three fingertips cover one column. Additional columns should also be felt by the first joint and by the second and third joints of these three fingers. The bimorphs should be positioned to obtain three stimulators per finger per column. A further improvement should result from using a more compliant bimorph since the vibrations of the present ones are damped out with only a slight deflection from the finger. Also, an increased deflection sensitivity would help reduce the difficult alignment problem encountered in mounting.

VI. CONCLUSION

The use of piezoelectric transducers to produce a compact, low-power consuming, dynamic embosser suitable as a reading device for blind people is shown to be definitely possible. The experimental embosser that was built was not entirely satisfactory, but the alterations required to yield considerable improvement are given. Some further experimentation will still be required to determine the optimum design of the embosser and to integrate the embosser and print-sensing probe.

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