A CLASS OF DIGITAL TRANSDUCERS UTILIZING MAGNETIC RECORDING

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Summary The need for direct digital transducers has been recognized for some time but remains largely unsatisfied. Magnetic recording could be applied for many applications. In this paper the techniques, capabilities and limitations of magnetic recording for measurement purposes are discussed including resolution and flux responsive readout methods. Some of the classes of variables which might be measured are outlined.

Introduction Nearly all data obtained in aerospace test programs is processed in digital form. Nearly all of it however is measured by transducers with an analog electrical output. Therefore, an electrical analog-to-digital converter must be provided somewhere. This is a complex and costly component so that a time-sharing switch or multiplexer is provided enabling the outputs from a large number of transducers to be coded by a single converter. There would be obvious advantages if the transducer output were in electrical digital form. (1)(2)

A few digital transducers have already appeared in the market. Perhaps the best known of these are the angle or shaft position encoders. These are generally “absolute” encoders in which a complete unique digital word is sensed for each increment of angle that can be resolved. A digital representation of angul6r position can also be obtained from an “incremental” coder. These are simpler than the “absolute” encoders in that only one track is required. The digital output word is obtained by counting the number of marks that have been passed in moving from one reading to a reference point. This is less desirable because it is necessary to pass a reference to obtain a reading whereas an “absolute” encoder can be read at any time. Angle encoders have been made using electrical contact brushes in conjunction with a conducting code wheel, by means of optically sensing clear and opaque spaces on the wheel or by magnetically sensing spots of permanently magnetized material. Angle encoders can and have been coupled to other sensors to form a complete digital transducer. Another class of transducers sometimes called quasi-digital are those which produce a frequency related to the value of a measured variable. A count of the number of cycles in a fixed period gives a digital representation of the measured value.(3)

This paper will describe how conventional magnetic recording techniques can be used to build an absolute type of digital transducer.

Selection of Method First the reasons for choosing magnetic recording should be considered.

For this purpose, a rather thorough search was made to discover how a digital transducer could be built at the present state of the technology. (4) The ideal digital transducer would be one which utilized a physical effect wherein the variable to be measured directly produces a coded output. No really suitable effect is known to exist. Freezing points, Curie Temperature, Barkhausen jumps and such properties of material offer only a few readily recognizable limiting values. Most of the physical effects useful for measurement are found to produce either a mechanical displacement or an electrical current. Therefore a means for encoding displacement preferably small displacements would thus be most generally useful as the basic element in a class of digital transducers for a number of different measured variables.

Description of Method The essential elements of a displacement transducer are shown in figure 1. This is seen to be identical to the situation in a multi-track magnetic tape recorder with the exception that the tape is replaced by a plated magnetic coating to give the dimensional stability required for precise measurement. Also, the heads must be capable of reading while stationary since many transducer applications would involve conditions where there would be little or no relative motion between medium and head.

Operation calls for an initial calibration procedure in which the medium is moved past the head group. Suitable currents are fed to each winding to write a unique code at each increment of displacement when it is reached. Then during a measurement these code words can be read to identify the displacement location or any other measured variable that it may represent. Thus, the recording medium becomes a stored look-up table for the transducer calibration.

Ordinarily the same head structure would be used for writing and for reading, thereby avoiding gap scatter and azimuth alignment problems. The general advantages and problems of the method may be summarized as follows:

Advantages

1. **Absolute Coder** Coding can be made absolute by providing a separate recording track for each bit in a word. Thus each increment of the coded measurement is positively identified whenever read. An incremental type could also be built by using only one or two tracks that could satisfy some requirements.

2. **In-Place Calibration** The calibration can be written for a completed instrument and so would include all internal errors and non-linearities. The transducer calibration could thus include linearizing, scaling and zero-shifting functions since the recorded code words could be in terms of any desired engineering units. A recalibration could be readily made.

3. **Versatile and Adaptable** The code as written, can be tailored to fit special missions. For example, certain parts of the range might be identified by a special code for all increments indicating no interest, while others would be coded for high resolution to precisely locate a transition. These special designations can be shifted or changed when desired by recalibration.

4. **Editing and Control Possible** Extra tracks might be added to allow special control or editing functions and the levels at which these occur could be changed at will.

5. **Fast Read-out-Low Power** Read-out can be made by short pulses so that power requirements can be kept small. This also permits adequate sampling of rapidly changing phenomena.

6. **High Resolution** Resolution capability is high so that in most cases a motion amplifying linkage to couple to a sensor should not be necessary.

7. **Small Moving Mass** The moving parts can be small and light so that reasonably good dynamic response is possible.

8. **Small Package** The essential parts need not be large, so that a small transducer is possible.

9. Simple Mechanism Writing and reading with the some device removes need for difficult adjustments of alignment for optimum operation and resolution.

Problems

1. **Friction and Wear** High resolution requires intimate contact between head and medium which implies a frictional force. This contributes to the hysteresis in a transducer and to wear which would limit its life. These effects can be minimized by design as will be discussed more fully.

2. **Flux-Responsive Readout** The fact that it is necessary to obtain a valid reading when there is no relative motion between head and medium requires a static reading or flux-responsive reading head. This is slightly more complex than conventional heads which read only a changing flux. It is necessary that the head output remain stable with time, temperature or any other variable other than recorded flux which might influence it.

3. **Precise Construction** Since high resolution does require intimate contact of the head and medium both must be rigid, both must also be extremely smooth and flat. Also, the guides and bearings controlling the motion of the medium must maintain contact and insure precisely repeatable movement so that track-to-track errors called "skew" in conventional recording cannot occur.

4. *Shielding* The ability to read from a stationary recording medium means that the head is also sensitive to other weak magnetic fields over a wide range of frequencies from zero or DC on up. A good overall magnetic shield must be provided to avoid sensitivity to orientation relative to the earth's field or to the location of magnetic objects in the vicinity. Stray fields from electrical devices near to the transducer must also be protected against.

5. Low Level Output Head output levels, when recording with high resolution are small so that amplification is required to reach logic levels.

Transducer Design This section will describe the design details of a digital displacement transducer and its component elements utilizing the magnetic recording technique.

Coding The specific code system to be used in a transducer would be influenced strongly by the functions that it would be designed to perform as indicated in Items 3 and 4 of the list of advantages in Section entitled, "Description of Method". However, for general applications where there is a progression of equal or nearly equal increments to 'De coded a "unit-distance" code or specifically the Gray code is especially well suited. This would be used with a non-return-to-zero (NRZ) recording technique wherein flux of one polarity represents a "1" while the other polarity represents a "0".

The desirable properties of the Gray code are that only one bit of a word changes at a time, that it effectively doubles the resolution, and that it is readily converted to the straight binary code which has been found most generally useful.

Some of these properties are illustrated in figure 2 which represents the idealized read-out flux that would be sensed by the heads on each of five tracks on which a Gray code had been written for the initial 26 increments of displacement. The solid lines indicate how the flux changes from one polarity to the other and the arrows indicate the locations and currents for the write head when this magnetization pattern was recorded. The properties of resolution doubling and single bit uncertainty are apparent in this representation.

Resolution Limit The limit of resolution is reached when the output change in moving from a “1” to a “0” is too small to be differentiated from the combined changes due to noise and instability. In the practical case the output from the head on the highest density track as a function of displacement would be more nearly sinusoidal than shown in the rectangular idealized diagram of figure 2 and its output would be:

$$e(x) = e_p \sin\left(\frac{2\pi x}{4X_m}\right)$$

where x is displacement and X_m is the length of the coded increment of displacement as shown in figure 3. Here “Δ e” indicates an error offsetting the output function and resulting in an error “Δ x” in the value of “x” at which the output indication changes from a “0” to a “1”. A maximum permitted error of $X_m/4$ would keep all errors less than X_m. Then

$$\Delta e = e_p \sin \frac{2\pi}{4X_m} \left(x = \frac{X_m}{4}\right) = \frac{\pi}{8}$$

$$\Delta e = +.38\, e_p \text{ as a maximum}$$

Recording Principles The magnetic principles which operate to control the value of ep have been studied by analysis and experiment to determine the optimum conditions. These are enumerated below:

1. Gap length should be about equal to or a little less than the minimum bit spacing. This, of course, refers to the actual effective gap length which is often 40 or more microinches greater than the “mechanical” or constructed gap length.

2. Medium thickness should be of the order of one half the gap length.

3. Medium should have as square a hysteresis loop as possible and coercivity should be high to reduce demagnetization.

4. Medium remanence should be as high as possible so that a large amount of flux can be obtained from a thin layer.

5. Separation between head and medium must be a very small fraction of the gap length. This requires that the head and medium surfaces be flat and smooth.

6. Recording current should be about 3/4 of that required to just saturate the layer of medium furthest back from the gap.

Recording Media A number of materials have been considered for the recording medium. The choice is limited by requirements for dimensional stability and surface flatness to metallic alloys generally plated onto a flat rigid base. The base should be as light as possible because its mass is the most important factor in the dynamic performance of the transducers. The base must also have excellent dimensional stability to play its important role as a part of a measuring instrument and to retain the flatness necessary for low head-medium separation. Quartz, silicon and glass would meet some of these requirements, but better wearing properties of the coating have been obtained with magnesium. Potential coating materials would include alloys such as Vical loy, Cunife and the various nickel-cobalt platings commonly employed with magnetic drums and disks. Best results here have been obtained with a plating similar to that on the metal tape made by Remington-Rand (Univac) for its early Uniservo recorders. Its important characteristics are listed below:

1 . Thickness	50-70 microinches
2. Coercivity-Hc	500 oersted
3. Remanence-BR	4500 gauss
4. BR/BM	.79

Flux-Responsive Heads The previous discussions have dealt with recording in terms of flux available to a reading head. The function of the head is to convert this flux efficiently to an output voltage. Since the heads must read while stationary, input energy or excitation is required to supply the output power. Flux responsive heads have not been widely used in conventional magnetic recording but many different forms have been devised. (5) The requirements of the heads for this application may be summarized as follows:

1. Flux responsive type - preferably operate with pulse excitation so that power input is minimized, reading time can be short and logic circuitry can be simplified.

2. Gap length to be determined by the desired resolution to be actually and effectively slightly less than equal to one recorded bit interval.

3. Track width - A practical compromise among various factors such as overall size, surface flatness and finish requirements and the fact that a wider track does collect more total flux. Azimuth misalignment considerations are less important because the same head is used for writing and reading.

4. Output - The available power should be as large as possible with relation to the available flux. The connected electronic circuitry must be matched to the output impedance.

5. Output stability - (a) The output at zero flux must be zero either as an inherent characteristic or as a result of external balancing circuits. Once established, this balance must be maintained over any specified ranges of time or environment. The failure to maintain such a balance is one of the most important factors in establishing the limiting resolution as defined in Section 2.2 entitled, “Resolution Limit”; (b) Sensitivity stability is also important since it would also influence the ratio to output shift which fixes the resolution capability.

6. Number of tracks - One for each bit of the digitized word used to identify the displacement location plus extras as desired for control or editing functions.

7. Environment - Materials and methods of construction must be such that gap length does not change significantly with specified environment. Location of gap with respect to a mounting surface should move in a uniform and reproducible fashion with changes in temperature, so that “temperature skew” is small with respect to the smallest coded increment.

8. Inter-track shielding - Inter-track coupling should be no greater than a small fraction of the total drift and error-producing output. However, since it is a DC field effect, a rather simple inter-track shield should be adequate.

9. Size - As small as possible for the specified number of tracks and track width.

Two methods of converting an unvarying flux to a voltage are being used in flux responsive heads.

In one, a Hall generator is included in the magnetic circuit, as shown in figure 4. A control current which may be DC, AC or a pulse is applied to one pair of orthogonal terminals (l_{c1}, l_{c2}) and output obtained from the other pair (E_{H1}, E_{H2}). The important characteristics of this type of head are:

1. Its output voltage is low but its impedance is also small so that step-up transformers can be used. Output can also be increased by as much as a factor of 10 by increasing the control current when pulsed for short periods.

2. The output with zero flux input is unstable with temperature and with the very low flux levels which must be sensed for high resolution; this constitutes a serious problem. Over a limited range of temperatures, thermistor compensation circuits can be used but must be individually fitted to each Hall element. In lower resolution applications, the output could be sufficient to avoid the need for temperature compensation.

The other type of head includes a magnetic modulator or gate in its flux path. Output is taken from windings like those in a conventional head. The general construction of this type head is shown in figure 5. Heads of this type may be operated in two ways. Most often, a sinusoidal excitation current is applied which causes a part of the magnetic circuit to saturate as indicated on the first line of (b) of figure 5. Thus, the reluctance “R” in the path of flux “ϕ_c” due to the recording is changed twice during each excitation cycle as indicated by the second line. ϕ_c then rises and falls as shown in the next line causing a voltage to be induced in the output winding. This output has a considerable component at the second harmonic of the excitation frequency. Because of stray coupling between the windings and non-linearity in the excitation current, there is a large fundamental and odd harmonic content of the excitation frequency also present at the output so that a band-pass amplifier is necessary to separate the desired component.

The other mode of operation might be termed pulse-interrogation. The stray coupling between excitation and output windings is minimized by coil and lead placement and a relatively fast-rising excitation pulse applied to change the head reluctance. By carefully minimizing coupling and providing a mutual coupling of opposite polarity to balance that which cannot be avoided, it is possible to obtain useful output pulses at quite high recording density. The characteristics of this type of head may be summarized as:

1. Output voltage is larger than from a Hall generator - but from a reactive source which can be controlled within limits by the number of turns in its output winding.

2. Output is proportional to frequency or rise-time of excitation up to point where output coil self-resonance is reached. At lower frequencies, output can also be increased by adding capacity to resonate the winding inductance.

3. Zero-flux output at the second harmonic is zero when all sources of flux are removed from the head and even harmonic distortion from the excitation. Then the change with temperature is also zero. With pulse excitation where zero output at zero flux depends on

rather precise balancing of stray fluxes, mechanical and magnetic changes with temperature can upset the balance, and so must be carefully controlled.

4. Output does not increase with increased excitation amplitude beyond the point where all of the saturable section is fully saturated. Increasing frequency or decreasing temperature increases the required excitation current so that its amplitude should be established in these “worst case” conditions.

Electronic Circuitry A great many variations in the associated electronic circuitry are possible, depending on the specific application and the system in which a transducer is to be used.

A generalized configuration suitable for a number of possibilities is shown in figure 6. This assumes that a programmer somewhere in the system would provide a series of “N” pulses whenever a reading from this particular transducer was desired. All of the heads would be read simultaneously and the resultant code word stored in a shift register. This would then be read out by the “N” interrogation pulses as a serial Gray code which a flip-flop would convert to a serial binary code. The transducer would thus require one individual input line from the programmer and would also be connected to power lines and an output line all of which could be common to a large number of transducers.

By slightly increasing the complexity, the individual line from the programmer could be replaced by several common lines and interrogation code recognition circuits, which might include the power supply so that this would only be called for when needed.

The actual circuits occupying the drive and amplifier blocks would be varied to suit the type of heads and mode of operation to be used.

It has been estimated that all of the components required for a 10-bit transducer could be packaged in micro-circuit form within a volume of one cubic inch.

Friction and Wear Tests have been made of the friction and wear characteristics of a number of materials that would be magnetically applicable as recording media or head pole tips. A number of lubricants which could be used over a wide temperature range (-40 to +100°C) have also been tested. These were also chosen to be ones that would not produce a thick enough film to reduce the recording resolution.

Friction coefficients vary from about .07 to .15 with the lowest values applying to lubricated conditions.

The nickel-cobalt plating is hard and wears well when processed so that it adheres well to its base. The longest wearing head material has been hard dense ferrite. A combination of ferrite with a smooth nickel-cobalt plating well bonded to a copper layer on a magnesium base seems capable of well over 10^6 cycles. Metal head pole materials such as Mumetal, Alfenol, and Sendust wear more rapidly with a tendency to gall, but a I ife of the order of 10^6 cycles seems possible with these when operated with a lubricant such as MIL-H-5606. Wear of ferrite materials has been too slight to determine any improvement when a lubricant is used. Abrasive dirt particles must of course be carefully avoided and can scratch even the hard ferrite head material.

Practical Transducer Characteristics One feasibility model was built sometime ago(6) which is shown in figure 7 as mounted in its test stand. This used commercial Hal I-type heads with gap lengths of approximately 0.5 mil. The recording density was 2500 bits per inch so that the operating resolution was 5,000 bits per inch or 0.2 mil per increment.

Two more advanced models are being built now that are believed to represent a practical approach to present state-of-the-art capability. These are much smaller as shown in figure 8. They are being designed to operate in a temperature range from -40 to +100°C and in the presence of accelerations of 10G. Both will use heads having 0.1 mil effective gap length so that the operating resolution is expected to be 20,000 bits per inch or 50 microinches per coded increment. Thus, the total range for a measurement resolution of 0.1% or 10 bits will be 0.05 inches.

One of these models will use modulator type heads of all ferrite construction. The other will have specially constructed Hall-type heads with thermistor compensation to operate without adjustment over a part of the total temperature range.

The mass of the moving parts will be approximately 3 grams and for the conditions stated, a frictional force of about 7 grams is estimated.

The electronic circuits for these models are being built on circuit boards for demonstration and testing. The circuits are however designed so that they can be revised readily in micro-circuit units to fit in a space roughly equal to that required for the displacement sensing parts.

Measurement Applications The basic displacement transducer can be used alone or coupled to various sensors to provide for different measurements.

Displacement Briefly, the transducer per se codes and reads displacement directly. The ranges permitting 0.1% resolution could be anything greater than .050 inch. Very long ranges would require special design considerations but could be handled with maximum resolution. Incremental methods would greatly simplify the measurement of large displacements by reducing the number of tracks required and the need to record long sections of like polarity.

Simple recording functions might also be added so that if a certain value or range of values were reached a recording on extra tracks could be made to show this or even the time of occurrence or value of some other variable of interest. The magnetized condition of the recording heads would show that a recording had been made, and it would be necessary to demagnetize them before readout. This is a simple procedure but does require moving the heads a few mils away from the medium or to a part of the range where the recording is not important.

Force A force transducer can be formed by adding a spring with a suitably stable deflection characteristic.

Acceleration Acceleration can be measured by reading the displacement of a spring-mass combination with appropriate damping.

Temperature Temperature may be sensed by the differential expansion between metals and a gas or liquid.

a. **Linear Expansion** The simplest adjunct to the displacement transducer to form a temperature transducer would be a rod of one metal with a low expansion coefficient; for example, Invar within another having larger change such as aluminum.

b. **Bimetal Thermometer** Bimetallic elements in various forms can also be used to produce a displacement. The disc shape seems well suited to producing the relatively small deflection and large force required in this case.

c. **Pressure Devices for Temperature** Temperatures are also measured by expansion of liquids or gases which produce a pressure and this is sensed at a short distance by a bellows or diaphragm identical to those used for pressure measurements.

Pressure A difference between pressures on two sides of a piston or membrane can be balanced by the deflection of a spring and the deflection is then a measure of the pressure difference. In diaphragms and capsules the spring and membrane functions may be combined in the same element.

A complete pressure transducer including the necessary electronic circuitry to provide serial digital output is shown in figure 9.

Other Variables The foregoing summarizes applications in the fields of measurement, which are basic. Other variables may also be measured, sometimes derived from these. For example, level can be represented by displacement of a float, flow is measured as a pressure difference, and others can be expected to materialize.

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Prior to this, the concept of a digital transducer using magnetic recording for a stored calibration table was originated by George Birkel and L. W. Gardenhire of Radiation Incorporated who have made it the subject of a patent application which is now pending.

The continuing assistance of Messrs. Gardenhire and Birkel and of many other Radiation personnel is gratefully acknowledged by the author.

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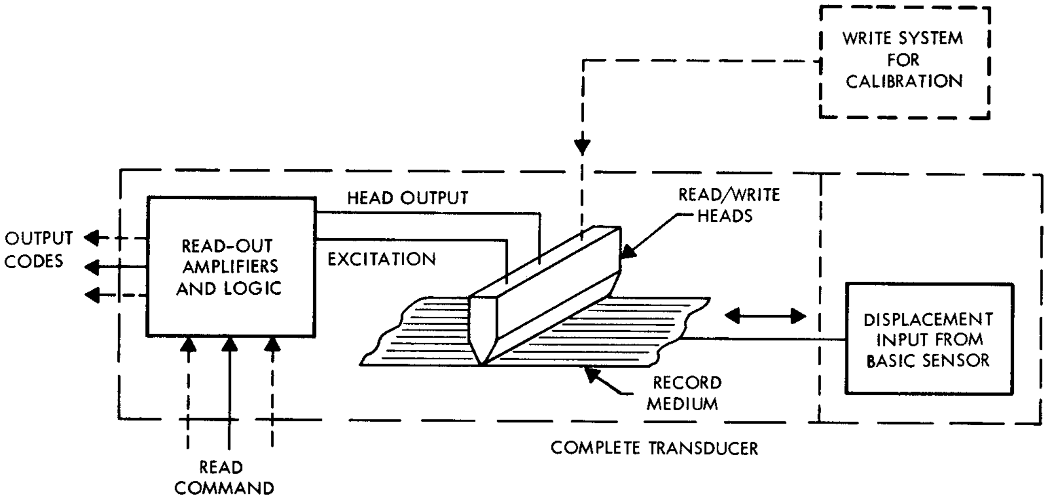

Fig. 1-Digital Transducer Elements.

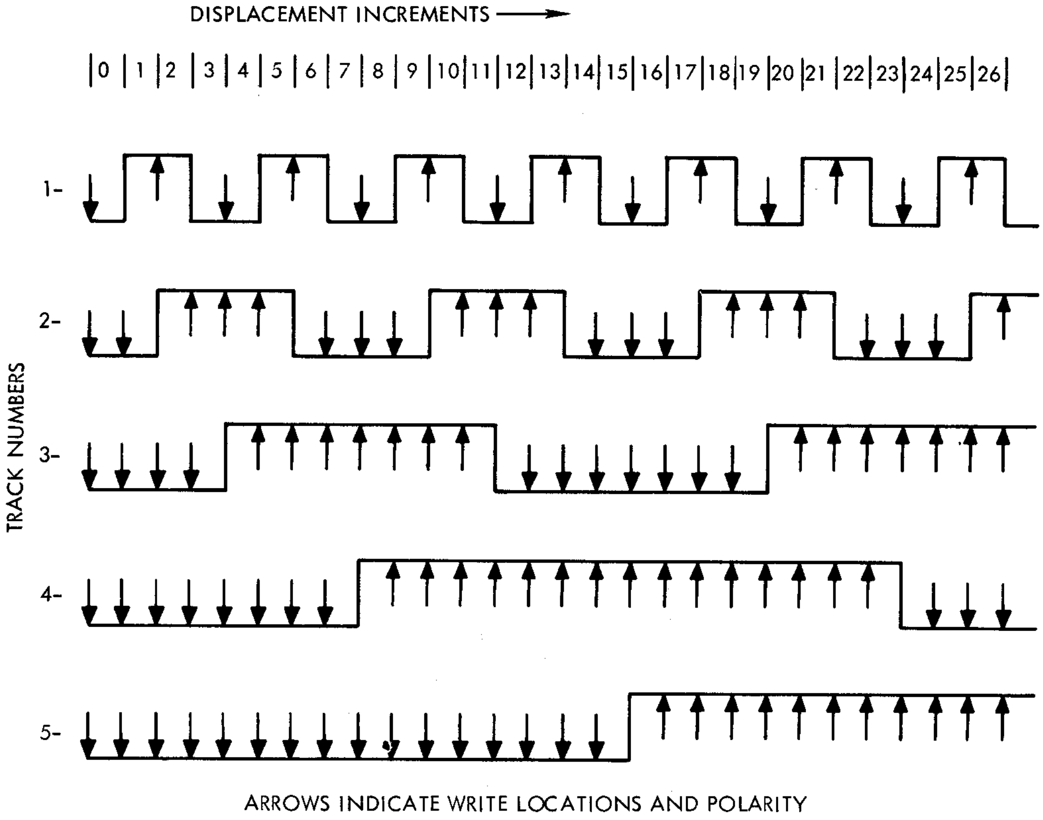

Fig. 2-Coding of Magnetic Tracks.

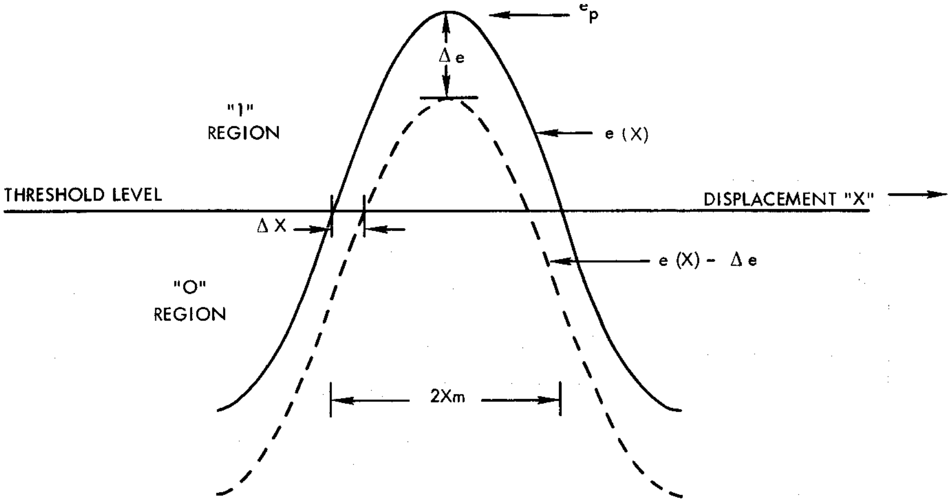

Fig. 3-Error Due to Shift in Output Level.

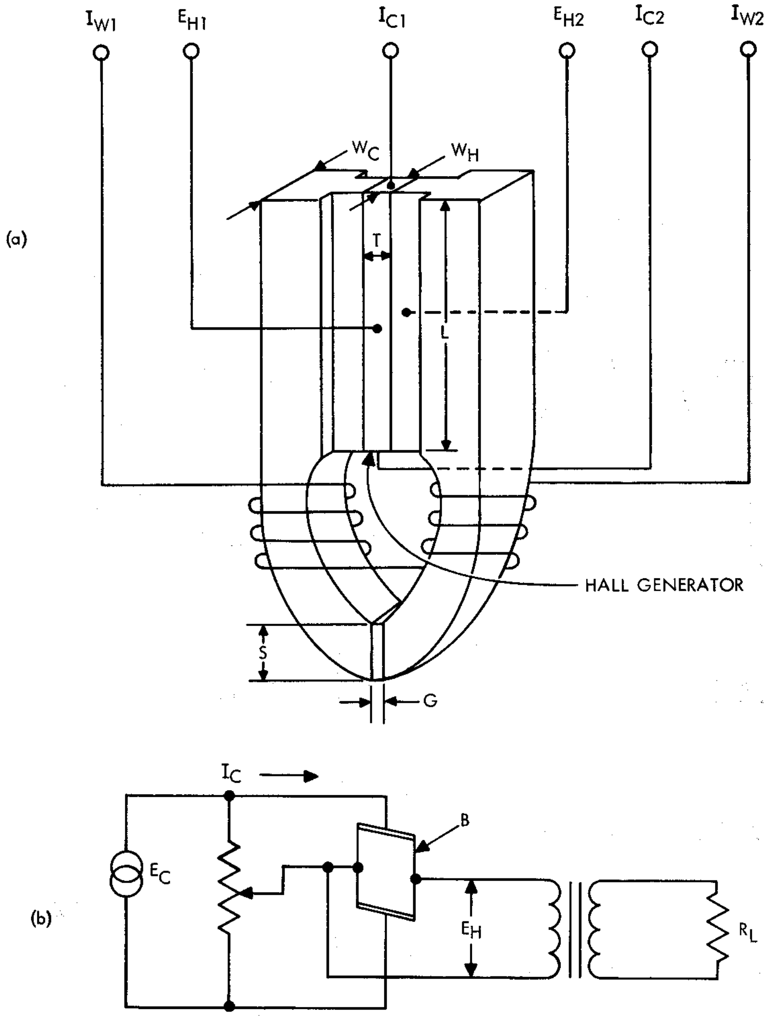

Fig. 4-Hall Generator Type Head.

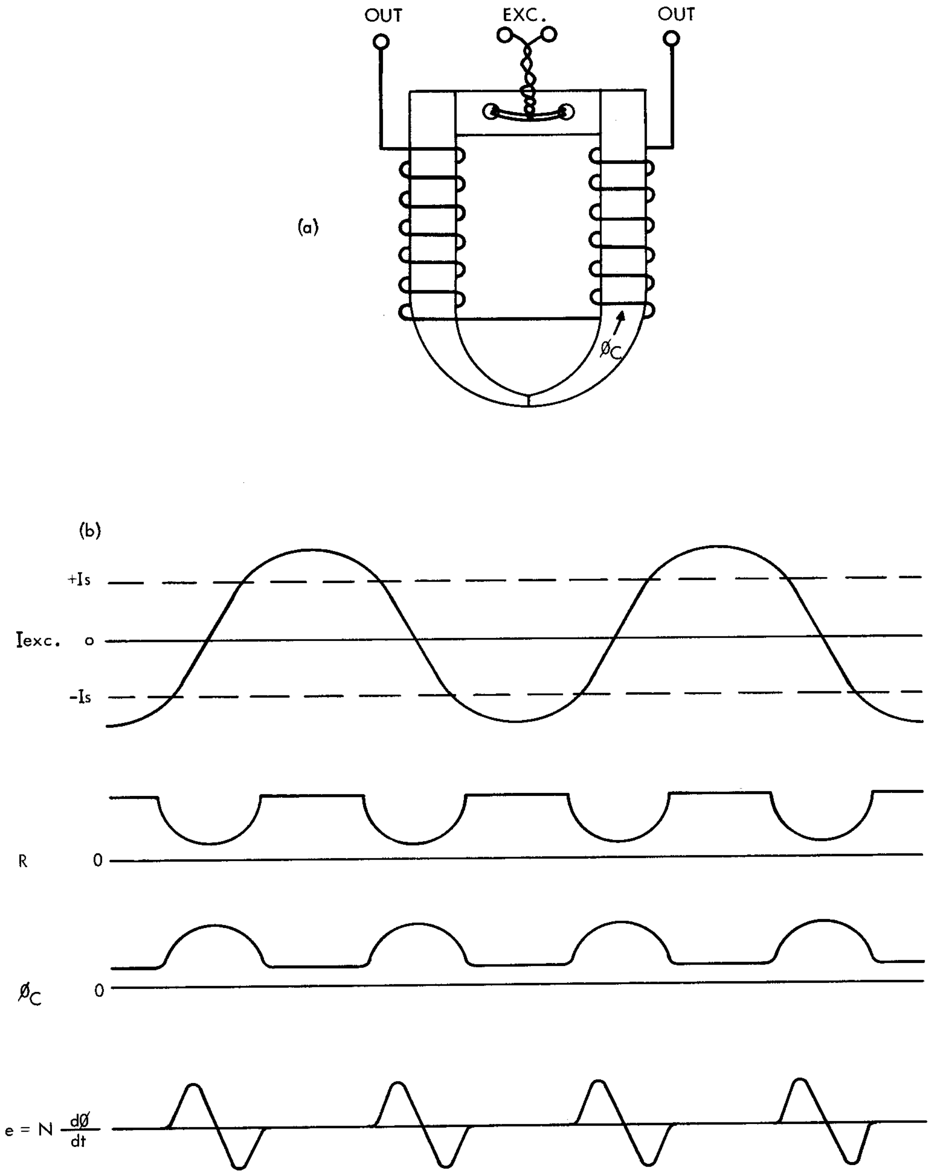

Fig. 5-Modulator Head and Waveforms.

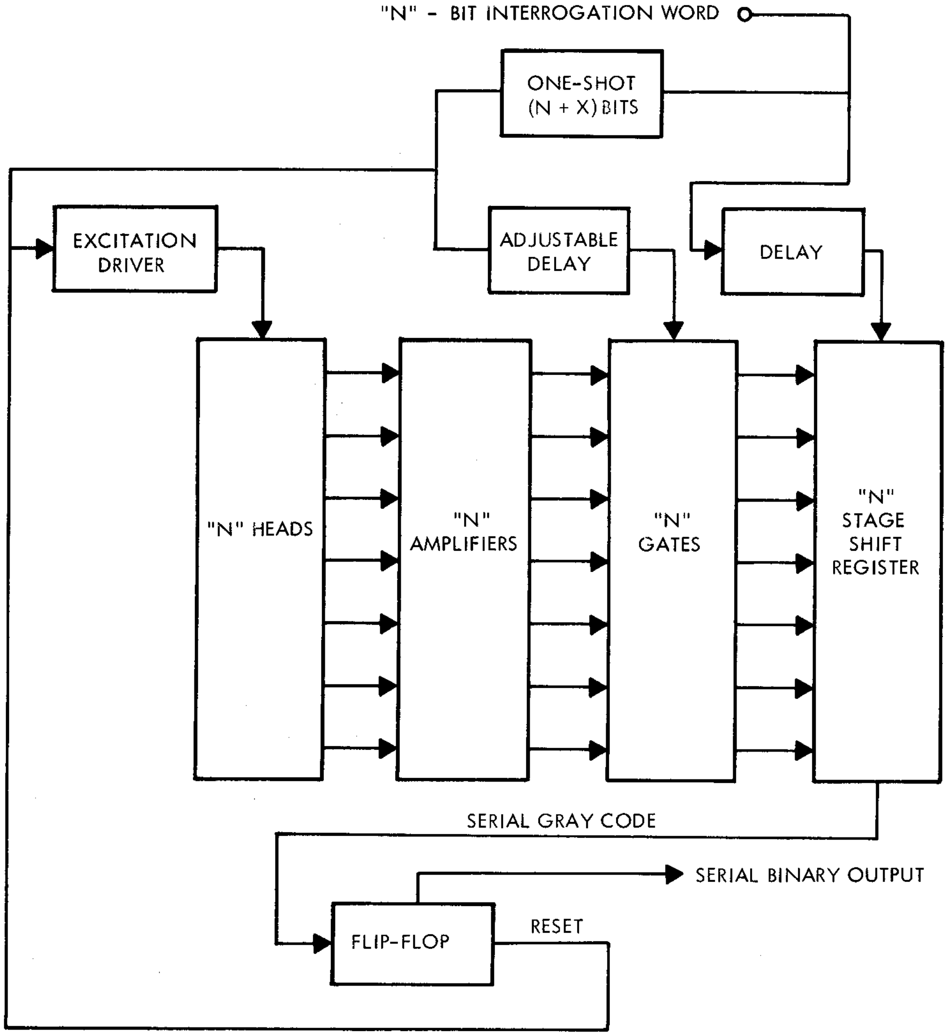

Fig. 6-Digital Transducer Electronics for Serial Binary Output.

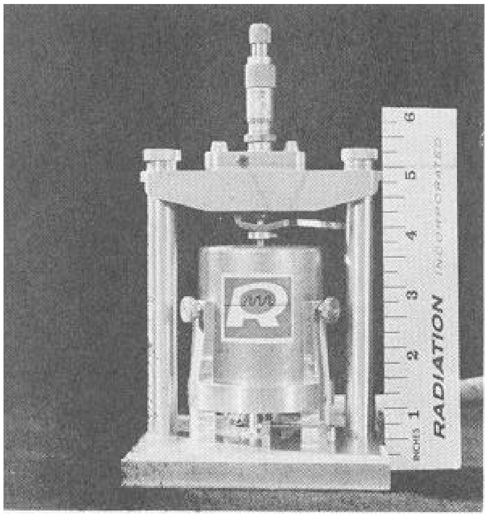

Fig. 7-Feasibility Model.

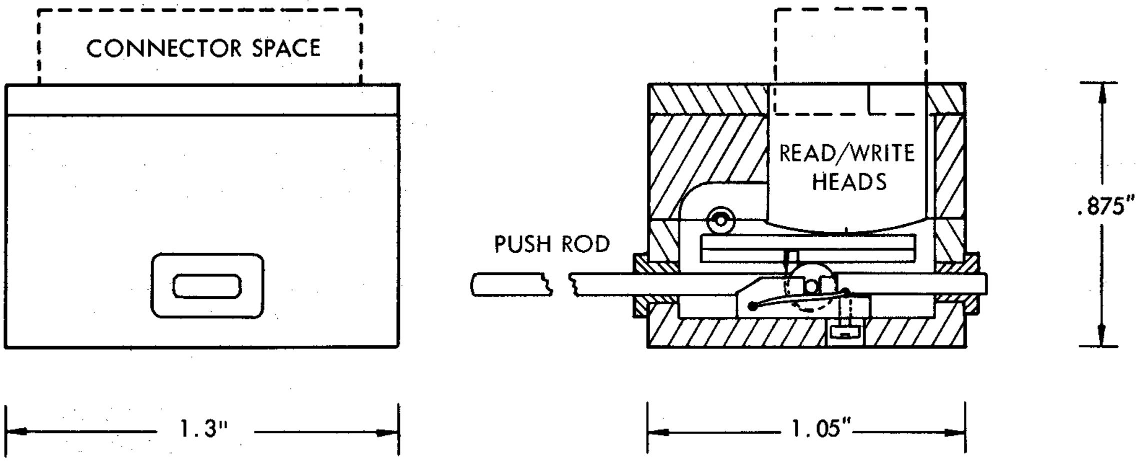

Fig. 8-Digital Displacement Transducer.

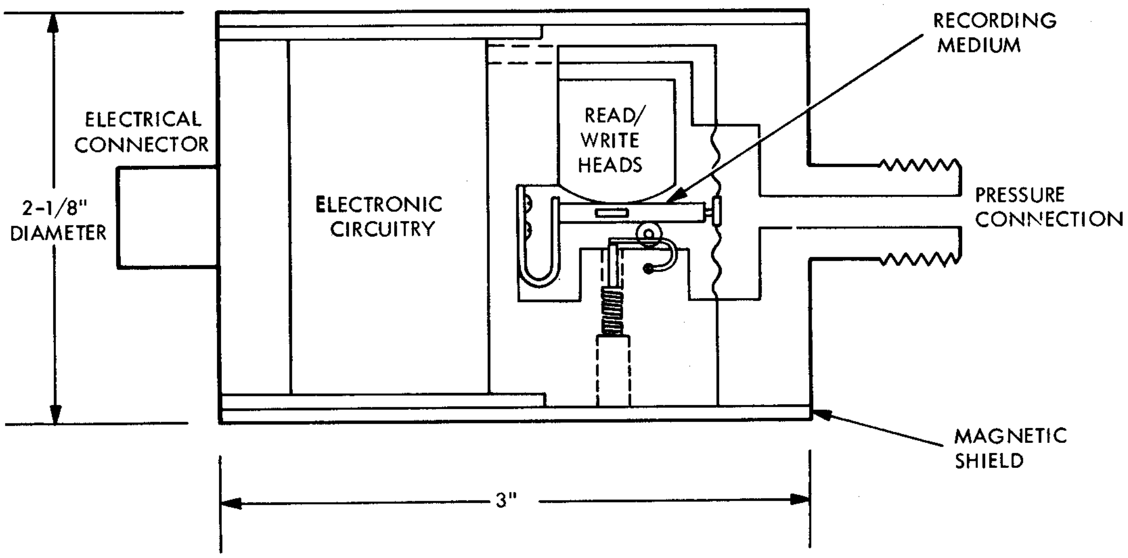

Fig. 9-Complete Digital Transducer for Pressure.