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TRANSUDCERS

FROM PHYSICAL EFFECTS TO ELECTRICAL MEASUREMENTS

by

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A false balance is an abomination to the Lord, but a just weight is his delight.

Proverbs 11:1

Ye shall do no unrighteousness in judgement, meteyard, in weight, or in measure. Just balances, just weights, a just ephah and a just hin, shall ye have.

Leviticus 19:35

1. INTRODUCTION.

In standard physical and engineering usage, the word "transducer" refers to a device which changes a particular kind of input signal into an electrical signal. For example, the input signal might be temperature, force, pressure, magnetic field, light intensity, pH, or shape.

The reason that measurement by transducers has become so pervasive is the extreme flexibility of dealing with signals once they are in electrical form.

Electrical signals are easily amplified, measured, filtered for noise, computer interfaced, and transmitted to distant locations. It is no wonder that transducers are being used for all types of measurement, for monitoring and control, and for remote sensing. The Voyager space probes of Jupiter and Saturn are in no small measure a triumph of the transducer.

Before we look at transducers themselves, a few words about some general aspects of electrical measurements is appropriate.
2. **ELECTRICAL MEASUREMENTS.**

(a) The potential divider

The existence of stable, high precision resistors enables us to divide down a voltage.

Consider the potential from a to c, \(V\), which is provided by a battery, say.

\[ V = i(R_1 + R_2) \]

by Ohm's Law

The potential from a to b, \(v\), when no current flows along wires e or f is given by

\[ v = iR_1 \]

by Ohm's Law

Thus, \(v = V \cdot r_1 / (R_1 + R_2)\)

i.e. the output voltage divides in the resistance ratio.

(b) The Potentiometer

The potentiometer is a potential divider, equipped with a galvanometer and an ammeter.

The galvanometer is a null detector, i.e. determines the absence of current.

The ammeter is used to monitor the current flowing through the resistance chain. If the point b is adjusted so that the current in the galvanometer reads 0, the potential to be measured \(v_m\) is proportional to \(r\), according to equation 1,

i.e. \(v_m \propto r\)

If a standard cell of known EMF, \(E_s\), is placed between e and f and the balancing value resistance is found to be \(r_s\), then again
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i.e. \( v_m = r \)

If a standard cell of known EMF, \( E_s \), is placed between e and f and the balancing value resistance is found to be \( r_s \), then again
Thus \( v_m / E_s = r / r_s \) giving the required result,

\[ v_m = (r / r_s) E_s. \]

(c) The Wheatstone Bridge

The Wheatstone Bridge consists of two potential dividers, and a galvanometer as a null detector.

When the galvanometer connected between \( a \) and \( b \) detects a null, i.e., no current, the potentials of points \( a \) and \( b \) are equal. From the divider equation 1.

\[ V \frac{R_1}{(R_1 + R_2)} = V \frac{R_3}{(R_3 + R_4)} \]

\[ R_1 / R_2 = R_3 / R_4. \]

Thus the condition for a "balanced" bridge is that the resistance ratios in the two arms of the bridge are equal.

(d) Automation

When the potentiometer or the Wheatstone Bridge are not balanced, the galvanometer detects an "error" signal. This signal can be amplified and used to drive a motor which adjusts a resistor in the circuit until balance is reached. Thus, nowadays, many potentiometers and bridge circuits are servo-controlled to operate automatically.

3. PASSIVE DEVICES.

Transducers may be roughly classified into active and passive devices. An active device is a converter of some source of energy into electrical energy. A passive device does not produce electrical energy, but controls its flow.

We now look at several passive elements and their applications.
Resistors

The resistance of a conductor depends on its physical state, e.g., shape, state of stress, or temperature.

1) Strain dependence

The resistance of a wire is given by:

\[ R = \rho \frac{L}{A} \]

\[ \rho = \text{resistivity} \]

\[ L = \text{length conductor} \]

\[ A = \text{area of cross-section...} \]

If the length changes by \( \delta L \)

the resistance change \( \delta R \) is given by:

\[ \frac{\delta R}{R} = \frac{\delta \rho}{\rho} + \frac{\delta L}{L} - \frac{\delta A}{A} \]

Now, the resistivity changes with deformation such that with an appropriate constant, \( \gamma \),

\[ \frac{\delta \rho}{\rho} = \gamma \frac{\delta L}{L} \]

The area of cross-section decreases with stretching also, so that in terms of Poisson's ratio, \( \sigma \),

\[ \frac{\delta A}{A} = -2\sigma \frac{\delta L}{L} \]

We find, therefore, that

\[ \frac{\delta R}{R} = (1 + 2\sigma + \gamma) \frac{\delta L}{L} = K \frac{\delta L}{L} \]

The overall gauge constant \( K \) has a typical value for thin films

\[ K = 2.5 \]

The Wheatstone Bridge circuit involved is:

(R is usually an identical but unstressed object, kept at the same temperature as the strain gauge.)

Examples

(a) Demonstrate the dangling nichrome wire and weight

(b) The Strain gauge:

Commercial Strain gauges are usually thin films laid down on an easily stretched substrate which is gluable onto a surface whose strain is to be measured.

Demonstrate the bending of a cantilevered beam.
We have seen how simple it is for a resistive transducer to measure strain; we may well ask, why do we want to measure strain. Three examples come to mind:

A Bourdon Pressure Gauge is a spirally rolled up metal tube blocked off at its inner end. Pressure into the tube causes it to unroll. The strain as it unrolls may be monitored with a sensitive strain gauge and the pressure monitored electrically.

A "load cell", which is in fact a strain gauge bridge may be placed in the arm of a crane. If the crane driver tries to lift too great a load, the gauge will issue an alarm signal. At the same time, of course, the weight of the load can also be displayed.

A strain gauge can measure force, because the force is related to the strain by Hooke's law. If force can be measured so can acceleration, using Newton's second law, $F = ma$. Thus we can make an accelerometer.

(y) The carbon microphone. Carbon granules are compressed together by a diaphragm which responds to the incident sound energy. The resistance drops as the granules are compressed. Telephone mouthpieces are nearly all carbon microphones.

(ii) Temperature Dependence

In most conductors, resistance increases with temperature. For a small temperature rise $\delta T$, the change in resistance, $\delta R$, is given by

$$\frac{\delta R}{R} = \alpha \cdot \delta T$$

$\alpha$ is the temperature coefficient of resistance.

Typically $\alpha \approx 0.004 \text{ K}^{-1}$ for most pure metals.

Again a standard bridge circuit can be used to measure small changes in resistance and hence temperature.

The calibrated platinum resistance thermometer is capable of measuring temperature to about $(1/1000)^\circ C$, and is an important thermometer. Several precautions are required for its use:

- (i) temperature induced changes in stress must be minimised
- (ii) thermal EMF's must be avoided; this is often achieved by using compensating leads, or by the use of AC in the bridge.

The wire in resistance thermometers can be made so fine as to be invisible. Such thermometers have been used to study turbulent fluctuations in air flows.

The thermistor is a resistive device whose resistance falls rapidly (exponentially) with increasing temperature. These are important in monitoring applications.

The forward resistance of certain solid-state diodes are important as low temperature thermometers.
(iii) Light dependence

Certain materials such as the semiconductor cadmium disulphide have a resistance which depends on light intensity. In such light dependent resistors (LDR), photons create electron-hole pairs which are available for conduction. The resistance falls from a few megohms to a few hundred ohms depending on the light intensity.

LDR's which typically cost about 50 cents, form the basis of most photographic light meters.

Capacitors

The value of a capacitor, \( C \), is related to its plate area \( A \), separation \( d \), and dielectric constant \( \varepsilon \), by

\[
C = \frac{\varepsilon A}{d}.
\]

We can see that varying the separation \( d \), changes \( C \). This can be monitored and used to detect motion.

Consider the bridge shown here. The bridge is driven by AC, and \( D \) is a (null) detector of AC, e.g., a headphone.

There are two capacitors in series with a common plate, which is capable of motion. When it moves one capacitor increases and the other decreases. The capacitive bridge balance condition is

\[
\frac{\varepsilon_1}{\varepsilon_2} = \frac{R_2}{R_1}
\]

Setting

\[
\frac{1}{\varepsilon_1} = \frac{d + x}{\varepsilon A}
\]

and

\[
\frac{1}{\varepsilon_2} = \frac{d - x}{\varepsilon A}
\]

we find that

\[
\frac{d - x}{d + x} = \frac{R_2}{R_1} \quad \text{i.e.} \quad x = \frac{d(R_1 - R_2)}{R_1 + R_2}
\]

where \( d \), which is very small, is the undisplaced capacitor separation.

Such a device can measure displacements of \( 10^{-9} \) m or less. We exhibit such a device, which measures \( 0.5 \) \( A^0 \) (1 hydrogen radius) per 0.1 gm weight of force.
Inductors

Many motion detectors depend on the motion of an inductor. Consider the arrangement shown in the diagram called the differential transformer. Alternating current flowing in the centrally placed coil, EF, induces equal and opposite EMF's in the coils AB and CD which are either oppositely wound or oppositely connected. If the coil EF moves up or down the induced EMF's in AB and CD no longer cancel. This signal is proportional to the displacement for small displacements.

An alternative arrangement is to have all coils fixed but move an iron core through the coils thereby varying the inductance. Such a device, often used in biological work, is called a linear variable displacement transducer (LVDT).

Devices for Measuring Magnetic Fields

(1) The **flip coil or rotating coil**.

A coil area A which rotates in a magnetic field has an EMF given by $E = B.A.\omega \sin \omega t$ where $\omega = 2\pi f$, $f$ = frequency of rotation. Can measure earth's field easily.

(2) The **Hall Probe**

When current flows down a conductor in a transverse magnetic field the charge carriers are pushed sideways. Their sideways motion causes a pile-up of charge on the surface of the conductor, transverse to both the current and the magnetic field. The electric field $E_t$ of this surface charge acts to prevent any further sideways flow.

On a charged particle the net sideways force is thus zero, i.e.

$$0 = (E_t + vB) \quad \text{i.e.} \quad E_t = -vB$$
(2) The Hall Probe (cont'd.)

The transverse voltage is given by \( V = E_t \cdot W \) where \( W \) is the width. Further the current is given by

\[
i = \rho \cdot v \cdot W \cdot D
\]

\( D \) = thickness.

We find therefore that

\[
V = R_H \cdot iB \quad R_H = 1/\rho \]

where \( R_H \) is called the Hall "resistance". (The charge density of the free carriers is \( \rho = ne \).

(3) Proton spin resonance

A proton spins like a spinning top. It also has a magnetic moment along its spin axis. In a magnetic field, the torque on the proton causes it to precess at a frequency \( f \) given by

\[
f = \gamma B
\]

\( \gamma = 2.675 \times 10^8 \text{ Hz/Tesla.} \)

A radio frequency field which has frequency given by this equation has energy absorbed from it. The measurement of the absorption frequency can be done using the protons (hydrogen nuclei) in a drop of water. As frequency can be measured to high accuracy \( B \) is determined precisely.

(4) The flux-gate magnetometer

Consider a coil wound around a toroidal specimen of iron and fed with alternating current of frequency \( f \). The relationship between flux \( \Phi \) through the iron and the magnetising current \( i \) is shown in the graph.

Suppose the coil is coplanar with a magnetic field \( B \), and a coil is wound around the diametric girth of the toroid. If the magnetic field \( B \) were zero, no nett magnetic flux would change through the diametric coil.
(4) The flux-gate magnetometer (cont'd.)

If B is non-zero, the core at a and b is partially magnetised. Therefore the AC current at an appropriate part of the cycle cannot increase the flux through the core at a as much as it can decrease it through b. Thus a pulse of flux goes through the diametrical coil. Similarly, another pulse appears later in the half-cycle with the roles of points a and b interchanged. A short reflection shows that the nett flux and hence the EMF in the diametrical coil is at frequency 2f. A detector of frequency 2f measures the magnetic field B.

The flux gate magnetometer is highly sensitive and is used in aerial survey for finding iron ore deposits.

4. ACTIVE DEVICES.

Thermocouple

When a loop is formed from two dissimilar metals and a voltage measuring device (potentiometer) is inserted in one of the arms, an EMF, called the Seebeck EMF, \( E \), is developed when the junctions are at different temperatures. The Seebeck EMF is tabulated for many pairs of conductors such as copper and constantan. The EMF increases by about 10 microvolts per degree. The cold junction is often held at ice temperature \( 0^\circ \text{C} \) and the so-called hot junction is made into a probe.

Thermocouples can be made very small and can be used to take the temperature of an insect, say.

A current fed into a thermocouple gives rise to the reverse phenomenon, cooling at one junction and warming at the other, i.e., acts as a refrigerator.

Thermopile.

The thermopile is a set of thermocouples in series, packed together side by side. The "cold" ends are connected to a cold block of metal, and the "hot" ends are blackened. A flux of radiation falling on the blackened ends gives rise to an easily measurable EMF.

The thermopile is used to measure thermal radiation levels. It is relatively insensitive to wavelength.
Photo-voltaic devices.

Semiconductor junctions when exposed to light produce an EMF. The EMF is related to the light intensity. Further, the reverse is true, putting a current through a semiconductor junction leads to light emission. The display device, the light emitting diode (LED) is such a junction.

Advanced photovoltaic devices are available to supply small amounts of electrical power from sunlight. Such devices are used on space probes and in remote telephone repeater stations, not to mention some new electronic watches.

Piezoelectric devices

Certain crystals exhibit piezoelectric phenomena, i.e. when these crystals are strained, they polarise electrically and a (large) voltage appears across opposite faces. Quartz is one of the most common piezoelectrics. Barium titanate is also a piezoelectric material which is usually sold in ceramic disk form.

Piezoelectric crystals are employed as gramophone pickup transducers, i.e., the wiggling of the needle in the groove strains the crystal which puts out a voltage for amplification. Fitted with a diaphragm, such a crystal can be used as a microphone. They can also be used as strain gauges.

Two piezo crystals can be placed together with a conducting foil between the surfaces of like polarity. The outer surfaces which have the opposite like polarity are electroplated and joined as shown. On compression a spark is thrown between the inner and outer electrodes. Such devices are used as ignition systems in internal combustion engines (lawn mowers) and as gas lighters.

Conversely, if a voltage is applied to the opposite faces of a piezo-crystal, the crystal will distort, e.g., expand or contract. This effect is exploited in piezoelectric headphones, in loudspeakers used as ultrasonic sound generators, and as hydrophones for underwater sounding.

Using both the forward and backward piezoelectric effects, a piezoelectric crystal connected to a high frequency oscillator can be made to mechanically oscillate resonantly. Such is the constancy of frequency of such oscillators, they can be exploited to set the frequency of radio stations, or keep time as in quartz crystal wrist watches.
5. NOISE REDUCTION.

The sensitivity of measuring transducers can, in principle, be made arbitrarily high using large amounts of electronic amplification. Unfortunately, lack of stability and noise sources make the amplification beyond a certain point vain.

One technique, called synchronous detection, using a lock-in amplifier can enormously increase the sensitivity of such measurements.

We shall illustrate this technique by a case-study of the detection of a weak source of thermal radiation using a thermopile. With no radiation entering the thermopile, a noise signal comes out of it. Let us amplify this noise signal, n, with an amplifier whose gain, G, switches from +G to -G at a frequency f derived from an external source. The output signal changes from +Gn to -Gn at frequency f. This signal is fed into an averager (capacitor), which in the course of time, averages this output signal to zero. This happens because this signal spends as much time positive as negative.

Now, consider the same apparatus with a radiation "chopper" in between the source and the thermopile.
The "chopper" disk with a hole in it rotates at a frequency $f$. A commutator on the disk shaft generates the frequency which switches the amplifier between $+G$. The hole in the disk is so placed that the radiation signal, $S$, only gets through when the amplifier has gain $+G$, thereby producing a signal $+GS$, which, unlike the noise, does not average to zero, as it always has the same sign.

Such synchronous detection technique which "throws away the signal" half the time, enables very weak signals to be detected, maybe even $1/10^3$ of the noise signal.

These techniques are widely used in physics and in astronomy. Tonight they were used in the capacitive bridge and the flux-gate magnetometer.

6. Reference.