Introduction to Ultrasonic Transducers

ULTRASONIC TRANSDUCERS

The name transducer is given to devices which convert energy from one form to another; and to convert acoustical signals into electrical signals. Some transducers performs the tasks of both transmission and reception, it must possess the characteristics of linearity and reversibility. A transducer is linear if it produces an exact equivalent in electrical terms of the incident acoustic waveform, and it is reversible if it has the ability to convert energy between the electrical and acoustical forms in either direction. The term reversible is frequently used, however, in a more specialized form, which denotes that energy is converted with equal efficiency in either direction.

The majority of transducers fall into two categories, those which employ electric fields in their transduction process and those which employ magnetic fields. Some are inherently linear whilst others have to be polarized to produce linear action. This arises from the fact that the force producing acceleration of the active mass of the transducer, which in turn causes acoustic radiation, can be directly proportional to or proportional to the square of the applied electric signal, depending upon the physical mechanism employed for transduction.

If the electrical signal is sinusoidal of the form

$$E(t) = E_e Sin(\omega t)$$

A square-law transducer produces a force proportional to

$$(E_e Sin(\omega t))^2 = \frac{1}{2} E_e^2 (1 - Cos(2\omega t))$$

i.e a steady component plus a sinusoidal component varying at twice the applied frequency. If now a steady polarizing quantity E_o together with the sinusoidal signal the force produced is modified, becoming proportional to

$$(E_o + E_e Sin(\omega t))^2 = E_o^2 + 2E_o E_e Sin(\omega t) + E_e^2 Sin^2(\omega t)$$

And if E_o is made much greater than E_e the final term of this expression can be ignored and an alternating force is produced which is a linear function of the applied sinusoid.

5-2 Piezoelectric Transducers

Consider first the direct piezoelectric effect. The surface charge induced on a slice of piezoelectric material is called the polarization charge p and is measured in coulombs/m^2. It is related to an applied stress T, measured in *newtons /m^2* by

$$p = Td \qquad (1)$$

Where d is the piezoelectric strain coefficient, defined as the charge density per unit applied stress, measured in coulombs/newton, when no external electric field is applied to the slice, i.e. under short-circuit conditions.

If now an electric field E measured in *V/m*, is applied to the slice, the electric flux density D, in *coulombs/m^2*, within it becomes

$$D = E\varepsilon + Td \qquad (2)$$

Where ε is its permittivity, measured in *farads/m*.

Now consider the converse effect. If an unstressed slice is subjected to an electric field it undergoes a mechanical strain S which is related to the electric field intensity by

$$S = Ed' \qquad (3)$$

Consideration of the princciple of the conservation of energy shows that $d = d'$ and yields an alternative definition for d, i.e. the mechanical strain produced per unit applied field, measured in *m/V* under condition of no load.

Applying a tensile stress T to the slice which possesses an elastic constant s, measured in *m/newton*, results in a total strain

$$S = Ts + Ed \qquad (4)$$

In a non-piezoelectric material eqns. (2) and (4) reduced to the well known relations.

$$D = E\varepsilon \qquad (5)$$

$$S = Ts \qquad (6)$$

When a compressive stress *(-T)* is applied, eqn. (4) becomes

$$S = -Ts + Ed \qquad (4\text{-a})$$

and the slice can be effectively clamped if S is made zero by balancing the strain produced by the electric field by the compressive strain. Under these conditions eqn. (4-a) gives

$$T = eE \qquad (7)$$

Where $e = \frac{d}{s}$ is the piezoelectric stress coefficient defined as the stress produced per unit applied field measured in *newtons/Vm.*

Equations (1) and (6) give

$$P = eS \qquad (8)$$

And an alternative definition for e, i.e. the charge density obtained per unit strain, expressed in *coulombs/m*^{2}.

5-3Electrostrictive Transducer

All dielectric materials exhibit the phenomenon of electrostriction but in the class of dielectrics known as feroelectrics, the effect is very pronounced. Within these materials electric dipoles are formed spontaneously which have a preferred orientation within certain localized regions or domains. Ordinarily, these domains are randomly disposed and the overall electric moment of the material is zero. Application of an electric field, however, cause the domains to become aligned with the field and the physical dimensions of the material alter. The mechanical strain is independent of the sense of the applied field, positive and negative fields producing the same strain; thus electrostrictive transducers are inherently non-linear and must be polarized to give true transducer action. Polarized electrostrictive materials have similar properties to piezoelectrics and are often referred to as piezoelectric.

Equations (1) to (8) and the system of coefficients and subscripts developed for piezoelectric materials can be used to describe the action of electrostrictive material also. There is one major point of difference, however; the value of the permittivity ε is dependent, though not linearly, upon the intensity of the polarizing electric field E_o. Hence D, d and e must be specified for a particular value of E_o.

5-4 Magnetostrictive Transducers

Magnetostriction is the magnetic analogue of electrostriction and occurs in all ferromagnetic materials, being strongly pronounced in iron, nickel, cobalt and certain polycrystalline nonmetals called ferrites.

The polarizing magnetic field can be provided in one of three ways:

(a) By incorporating a permanent magnet in the transducer housing in contact with magnetostrictive element,

(b) By winding a coil carrying a direct current round the element,

(c) By heating the element and allowing it to cool while subjecting it to a high intensity magnetic field.

A current i amperes circulating in a coil of N turns produces in a closed ferromagnetic circuit a magnetic field of intensity, measured in *ampere turns/m*,

$$H = kNi/l$$

Where l is the length of the magnetic circuit and k is a constant whose value depends upon its configuration. This field produces in the circuit a magnetic flux density

$\beta = \mu H$

Where μ is the permeability.

The resulting strain S is proportional to the square of this flux density

$$S = K\beta^2 \qquad (9)$$

Where K is the material constant measured in m^2/Wb^2 which is positive for a material which expands upon magnetization and negative for one that contracts.

The flux density has two components β_o and β_e, the polarizing and alternating component rspectively.

Eq. (9) therefore contains an alternating component

$S = 2K\beta_o\beta_e$

or

$$S = \beta\beta_e \qquad (10)$$

Where $\beta = 2K\beta_o$ is the magnetostrictive strain coefficient, defined as the strain produced per unit applied flux density and measured in m^2/Wb.

A tensile stress t, measured in *newtons/m*^{2}, also applied to the specimen results in a total strain

$$S = Ts + \beta\mu H_e \qquad (11)$$

Where s is the elastic constant

When a mechanical stress T is applied to a magnetostrictive element the resulting magnetic flux density is

$$\beta_e = \mu\beta T \qquad (12)$$

Which leads to the alternative definition for β, namely the magnetic field intensity produced per unit applied stress measured in *ampere turns/newton/m*.

If an external magnetic field is also applied, the flux density is increase to

$$\beta_e = \mu H_e + \mu\beta T \qquad (13)$$

The specimen can be operated under clamped conditions by applying a stress which produce a strain equal and opposite to that produced by the magnetic field. S in eq. (11) is zero and

$$T = \beta\mu H_e / s \quad \text{or} \quad T = A\beta_e \qquad (14)$$

Where $A = \beta / s$ is the magnetostrictive stress coefficient defined as the stress produced per unit flux density, measured in *newtons/Wb*.

Equation (10),(11),(12),(13), and (14) are magnetostrictive analogies of eqns. (3),(4),(1),(2), and(7) respectively. From these, analogies between various magnetostrictive and piezoelectric coefficients can be drawn, as in table (1).

Magnetostrictive coefficient	Piezoelectric coefficient
H	E
B	D
μ	ε
$\mu\beta$	D
μA	E