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Magnetic Particle, Hysteresis, and Eddy-Current Brakes and Clutches

All three of these brake or clutch types have no wearing parts because the torque is developed from electromagnetic reactions rather than mechanical friction. Electronic controls and a rectifier to provide direct current are required, however, for their operation. They are, nevertheless, not usually referred to as electric brakes because that term had been reserved earlier to denote friction brakes which are electromagnetically activated: those in which an electric current through a coil induces a magnetic field that engages a shoe and drum, as pictured in Chapter 4.

Because particular construction variations from manufacturer to manufacturer can have a strong effect on the performance characteristics of these brakes in terms of magnetic fringing and local variation of the electric fields, we limit our discussion of the theoretical background of these brakes to the underlying equations only. This is consistent with the design practices associated with these brakes. They are often designed in the laboratory by a combination of theory and trial and error because our present theory is not adequate to handle small geometric effects on the electric and magnetic fields between conductors that are very close to one another. Incidentally, these theoretical shortcomings are also evident in present-day design procedures for high-frequency antennas.

Since these formulas are not presented with sufficient detail for the reader to design magnetic particle, hysteresis, or eddy-current brakes, they will not be summarized at the end of the chapter.

I. THEORETICAL BACKGROUND

The basic equations that define the theory used in explaining the generation of eddy currents and of hysteresis loops are presented in the remainder of this section. A more complete discussion of the theory, beginning with Maxwell's equations, equations (1-1), along with the derivation of the subsequent relations may be found in Stratton [1] and in Lammeraner and Starl [2]. Units for the quantities involved will be given according to the MKS system (acronym for meters, kilograms, seconds).

Maxwell's equations (1-1) in vector form are generally taken as the starting point for the study of the interdependent electric and magnetic fields in free space sufficiently far from their generating electron flows. These two vector equations are

$$\begin{aligned} \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0 \\ \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J} \end{aligned} \tag{1-1}$$

in which **i**, **j**, and **k** denote unit vectors in the positive *x*-, *y*-, and *z*-directions, respectively.

Here, **E** denotes the electric field intensity (volts/meter), **H** the magnetic field intensity (ampere-turns/meter), **B** the magnetic induction (webers). **J** the current density (amperes/meter^2, and *t* the time (seconds); the operator ∇ is defined by

$$\nabla \equiv \frac{\mathbf{i}\partial}{\partial x} + \frac{\mathbf{j}\partial}{\partial y} + \frac{\mathbf{k}\partial}{\partial z}$$

It can be shown [1] as well that the following relations hold in free space:

$$\begin{aligned} \nabla \cdot \mathbf{B} = 0 \qquad &\text{and} \qquad \nabla \cdot \mathbf{D} = \rho \\ \mathbf{D} = \varepsilon_o \mathbf{E} \qquad &\text{and} \qquad \mathbf{H} = \frac{\mathbf{B}}{\mu_o} \end{aligned} \tag{1-2}$$

where ρ denotes the charge density (coulombs/meter^3) and constants ε_o and μ_o denote the electric and magnetic permeabilities of free space, respectively. In the MKS system, the units of ε_o are farads/meter and the units of μ_o are henries/meter.

Within an isotropic and homogeneous material, equations (1-1) are replaced by the following set of equations:

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \quad \nabla \times \mathbf{B} - \varepsilon_o \mu_o \frac{\partial \mathbf{E}}{\partial t} = \mu_o \left(\mathbf{J} + \frac{\partial \mathbf{P}}{\partial t} + \nabla \times \mathbf{M} \right)$$
$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \cdot \mathbf{E} = \frac{1}{\varepsilon_o} (\rho - \nabla \cdot \mathbf{P}) \tag{1-3}$$

where polarization vector **P** and magnetization vector **M** are defined by

$$\mathbf{P} = \mathbf{D} - \varepsilon_o \mathbf{E} \qquad \text{and} \qquad \mathbf{B} = \mu_o (\mathbf{H} + \mathbf{M} + \mathbf{M}_o) \tag{1-4}$$

because both **P** and **M** vanish in free space. The last two of equations (1-2) are replaced by

$$\mathbf{D} = \varepsilon \mathbf{E} \qquad \text{and} \qquad \mathbf{H} = \frac{1\mathbf{B}}{\mu} \tag{1-5}$$

in which ε and μ are called the inductive capacities of the medium.

After adding Ohm's law, which is that

$$\mathbf{I} = \frac{\mathbf{E}}{\Omega} \tag{1-6}$$

in a medium having resistance Ω(ohms), we have all of the relations that together explain the generation of an eddy current **I** and a hysteresis loop for **H** in a homogeneous, isotropic medium [2].

The electric current flowing across a surface in the material is given by

$$I = \int_S \mathbf{J} \cdot \bar{\boldsymbol{n}}\, ds \tag{1-7}$$

In our discussion of electric brakes that induce a magnetic field, which is the primary source of the braking torque, we shall be concerned only with equation (1-4) and the equation for the work done by cyclic changes in the magnetic induction within a material volume V, which is

$$W = -\int_V dv \oint \mathbf{B} \cdot d\mathbf{H} \tag{1-8}$$

Magnetic induction **B** in the material is induced by an external **H** field, which in turn is usually generated by a current **I** in a coil of wire according to

$$\mathbf{H} = NI \tag{1-9}$$

where N is the number of turns of wire in the coil.

Calculation of work W according to equation (1-8) involves substituting for **B** from equations (1-4) to get

$$W = -\int_V dv \left(\frac{1}{\mu} \oint \mathbf{B} \cdot d\mathbf{B} \right) \tag{1-10}$$

which is nonlinear because of the interdependence of **M**, μ, and **B**. Depending on the material, the relation between **B** and **H** may appear as in Figure 1(a) or (b). It is the nature of these curves that determines the torque-control current

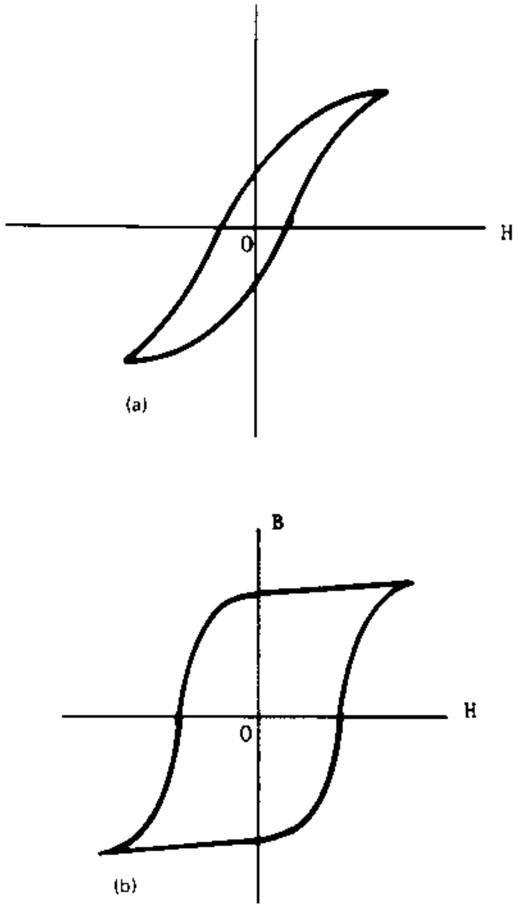

FIGURE 1 Representative hysteresis loops for (a) low-loss material and (b) high-loss material.

curve, represented by Figure 2, for a hysteresis brake. Techniques for generating the cyclic behavior of B and using it for braking are discussed in the sections devoted to individual brake designs.

Eddy currents are generated within a conducing material whenever the magnetic field changes, as implied by the relation for **J** in equations (1-3). For design purposes, the power P_e lost due to cyclic eddy-current variations in a flat plate may be estimated from

$$P_e = \frac{\pi \delta f \mathbf{B}_{\max}}{(Ck)} \tag{1-11}$$

where δ represents the plate thickness, f is the frequency of the cyclic variation, k is the specific resistance of the material, and C is a dimensional constant.

Although these relations indicate that hysteresis and eddy currents occur together in eddy-current and hysteresis brakes, one or the other may be made to dominate by selecting a material with the proper combination of μ and k.

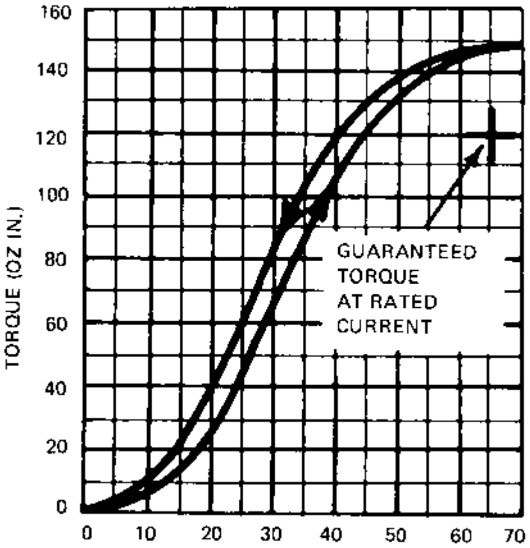

FIGURE 2 Typical torque control current curves for a hysteresis brake. Arrows indicate increasing or decreasing coil current. (Courtesy of Magnetrol, Inc., Buffalo, NY.)

II. MAGNETIC PARTICLE BRAKES AND CLUTCHES

These brakes are available in a range of sizes that include the 100-lb-ft model shown in Figure 3 and the 8-lb-ft model shown in Figure 4. Since these configurations are equally suited for clutches, they may be combined to form clutch-brake combinations, as in Figure 5. When used as a clutch, the unit has two moving parts; when used as a brake it has only one.

When used as a clutch, the configuration is as represented by the schematic in Figure 6(a). The input shaft is attached to a cylindrical drum, termed the *outer member*, or OM, which encases a smaller, inner cylinder, termed the *inner member*, or IM, which is attached to the output shaft. A dry, finely divided, proprietary magnetic material is contained in the region between the

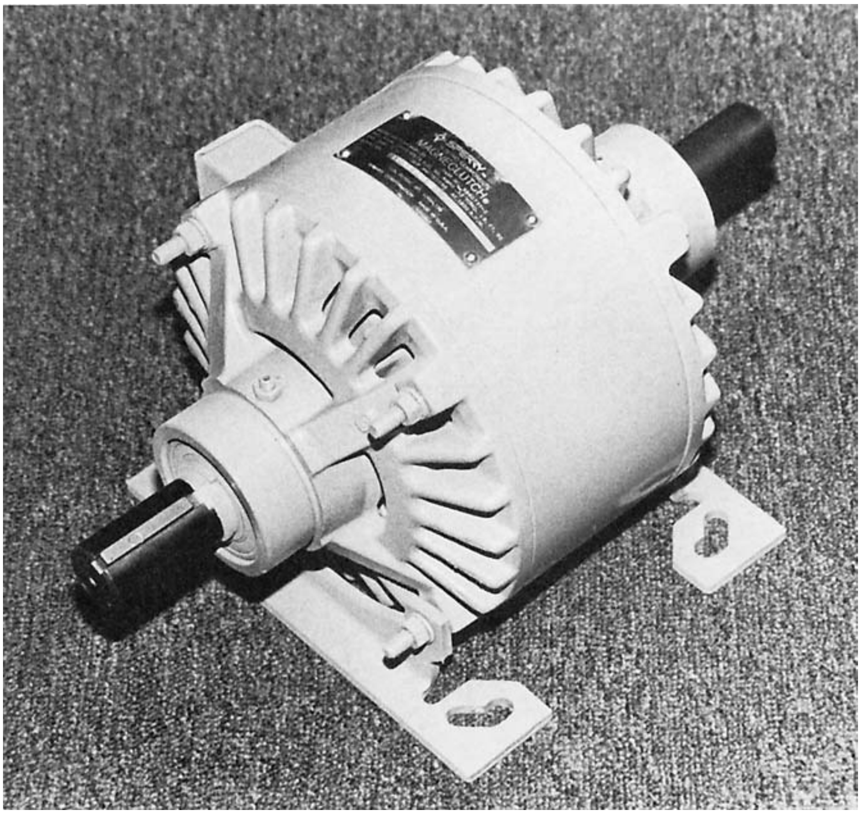

FIGURE 3 Magnetic particle brake with a 100-lb-ft capacity. (Courtesy of Sperry Electro Components, Durham, NC.)

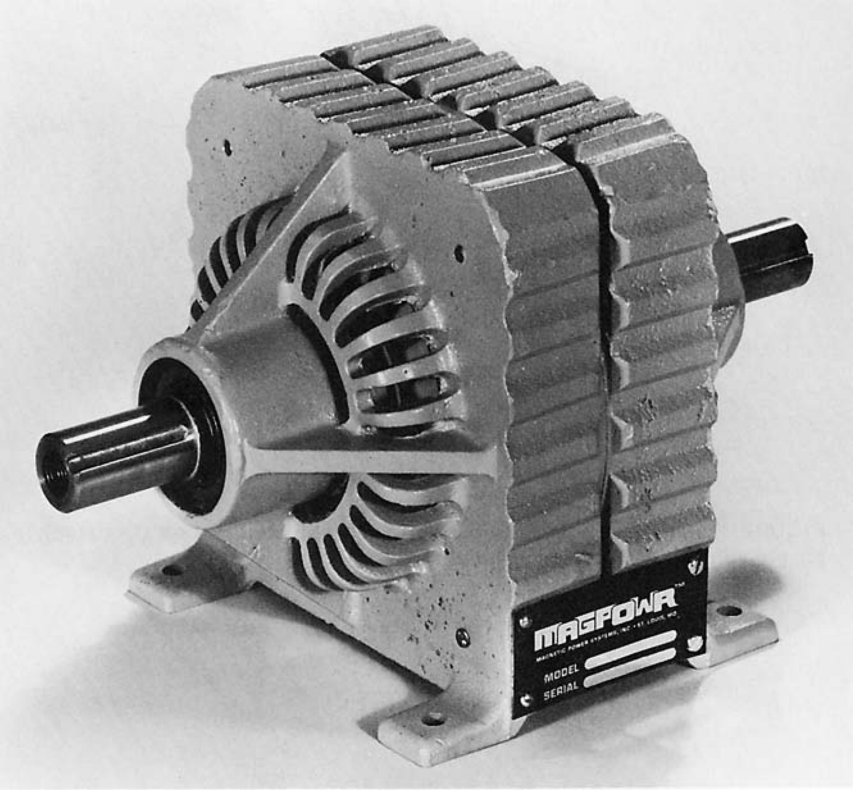

FIGURE 4 Hysteresis brake with a 8-lb-ft capacity. (Courtesy of Magnetic Power Systems, Inc., Fenton, MO.)

OM and the IM. The brake configuration differs from the clutch only in that the IM is rigidly attached to the brake frame.

An electromagnetic coil outside the OM and concentric with it is used to activate the brake or clutch. When the coil in energized by passing current through it a magnetic field is established which causes the particles to bridge the gap between the IM and the OM and form links between the two, as represented in Figure 6(b). These links are along the magnetic lines of force, which are made nearly perpendicular to the OM by the configuration of the OM and the coil housing, as shown in Figures 6 and 7.

Both the shear and tensile stresses in these links resist relative motion between the IM and the OM and so transmit torque for the brake/clutch. These shear and tensile stresses developed are dependent on the coil current

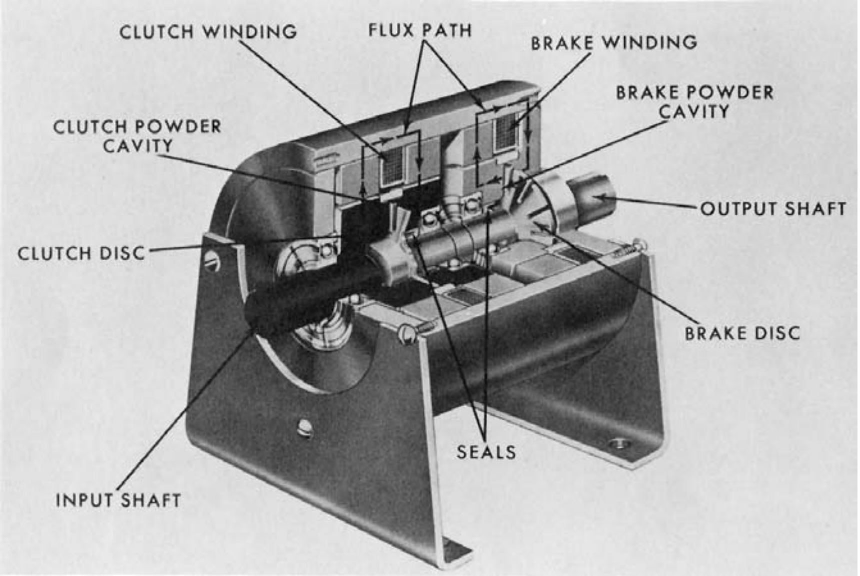

Figure 5 Magnetic particle clutch and brake combination. (Courtesy Simplatrol Dana Industrial, Webster, MA.)

and are independent of rotational speed. Typically, the torque varies with the coil current, as illustrated in Figure 8, while the torque remains constant regardless of the rotational speed of the OM, as shown in Figure 9.

III. HYSTERESIS BRAKES AND CLUTCHES

Construction of a hysteresis clutch, shown in Figure 10, differs from that of a hysteresis brake only in that the outer member, termed the OM, is prevented from rotating. This schematic implies that in the brake configuration the coil winding occupies a greater portion of the base of the cup-shaped OM, as indicated in the schematic in Figure 11.

In either construction the cup-shaped OM is fitted with a central post that fits within the smaller cup-shaped inner member, termed the IM. Magnetic field variation is accomplished by reticulating the OM wells and post, as indicated in Figure 12(a) to produce an alternating set of north and south magnetic poles when the OM is magnetized by current flowing through the coil in its base. At any instant the magnetic field from these poles induces a set of opposite poles in the walls of the IM. Rotation of the IM is, therefore,

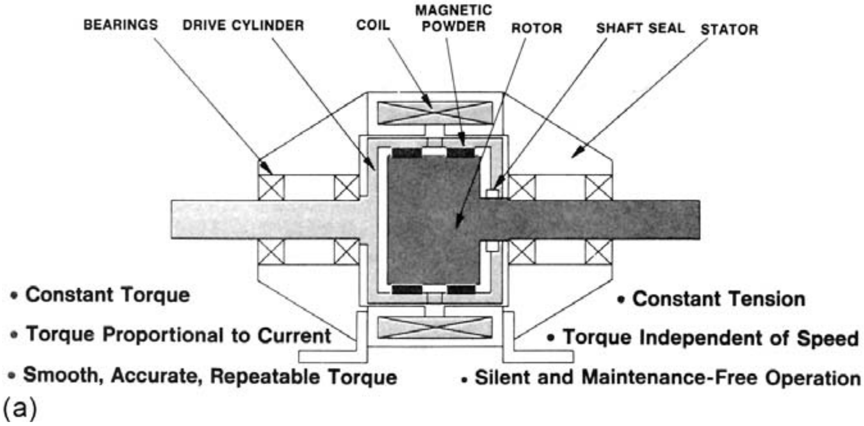

Figure 6 Schematic of a magnetic brake/clutch to display its operation. (a) Magnetic particle clutch. (b) Input shaft "R" and output shaft "N" are positioned within the electromagnetic coil. Magnetic particles lay loosely between input and output components. No current is applied to the coil. No torque is transmitted. (c) Here maximum current energizes the coil. The clutch now operates at 100% of clutch rating. Full transmission of torque occurs. Depending on coil current, any level between 0 and 100% torque transmission is possible. (Courtesy Magnetic Power Systems, Inc., Fenton, MO.)

opposed by the magnetic force between the induced poles in the IM and those in the OM because it disturbs this arrangement by forcing opposite poles apart and similar poles together. As the rotation continues due to external shaft torque, the magnetic field from the OM changes the magnetization of each point in the magnetized region of the IM so that the magnetic induction B at any point on the walls of the IM traverses the hysteresis loop as that point moves under the north to south to north pole of the OM's outer shell.

By forming the IM from a magnetically hard material (one that resists a change in magnetization as indicated by a small value of μ) which also has a large area enclosed by the hysteresis loop, the manufacturer can assure relatively large losses in the brake. The energy extracted from the input shaft in this manner heats the IM, which must be cooled to maintain the performance of the brake.

Figure 13 clearly shows that the braking torque is maximum for low rotational speed, including 0 rpm, and that as the speed increases a critical point is reached which corresponds to the maximum power that can be dissipated by the brake, based on its internal construction and the ambient temperature.

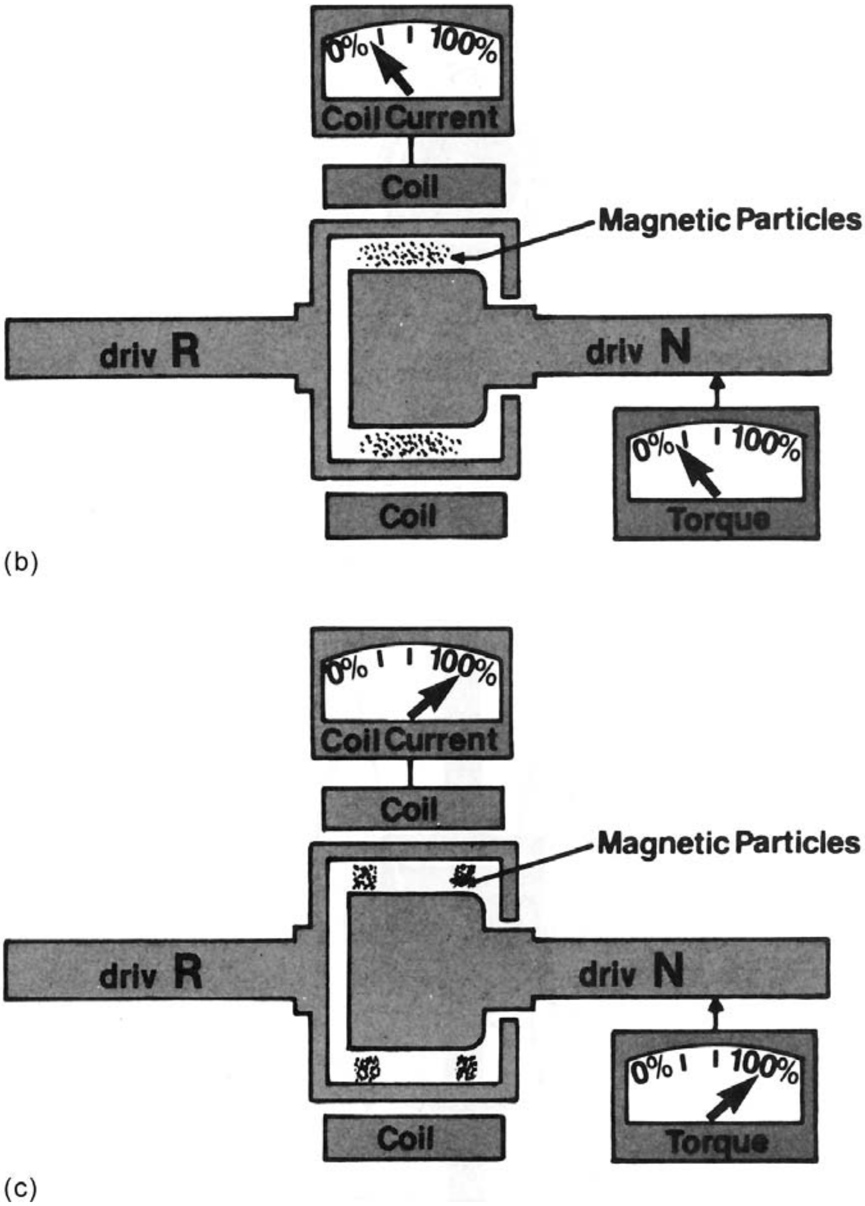

FIGURE 6 Continued.

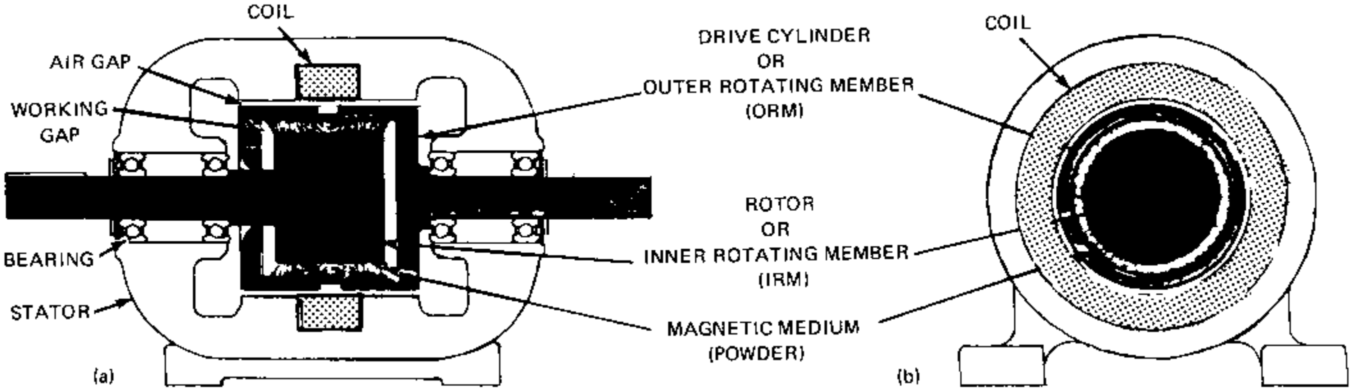

FIGURE 7 Magnetic lines of force linking the outer member (OM) and the inner member (IM). (Courtesy of Sperry Electro Components, Durham, NC.)

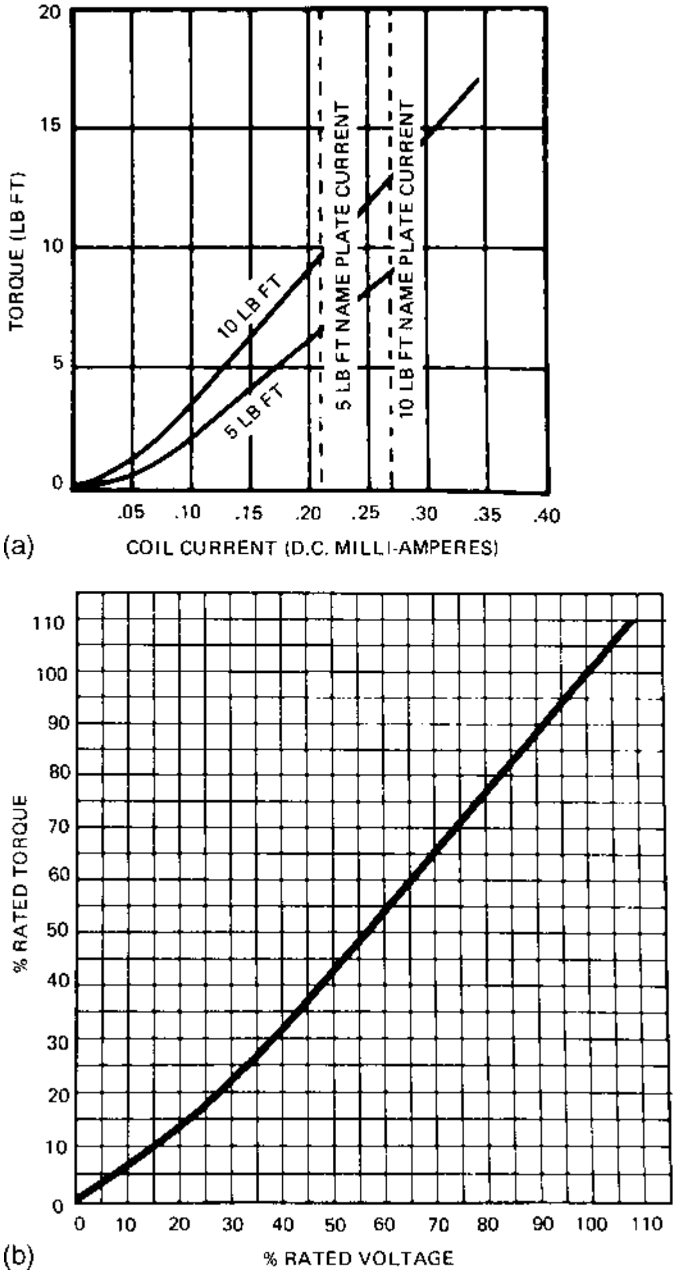

FIGURE 8 (a) Torque current curve for a particular brake; (b) torque voltage curve for a series of magnetic particle brakes. (Courtesy of Sperry Electro Components, Durham, NC, and Simplatrol Dana Industrial, Webster, MA.)

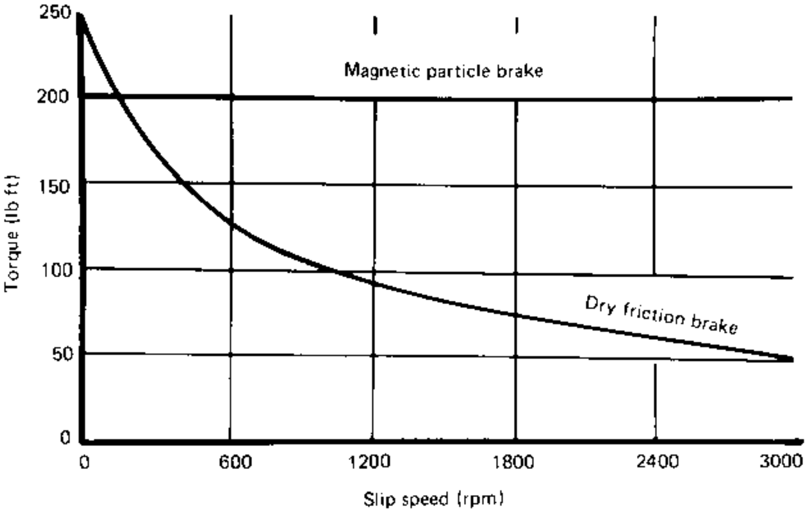

FIGURE 9 Torque-slip speed curves for dry friction and magnetic particle brakes (also clutches).

Beyond this point the torque decreases rapidly, as shown in the slip torque versus speed curve in Figure 13(a). Comparison with Figure 13(b) correctly implies that the shape of the decreasing-torque portion of the curve to the right of the critical point reflects both the change in the hysteresis loop with increasing temperature and the heat transfer characteristics of the cooling system (i.e., whether air or liquid and the temperature and velocity of the cooling medium). When these conditions are fixed the shape of the curve remains qualitatively invariant. Thus, as the brake torque increases from one size of brake to another, that portion of the curve to the left of the critical point decreases unless improved cooling is used to move the concave portion of the curve upward and to the right, thus moving the critical point to the right.

The magnitude of that portion of the curve which is independent of rotational speed to the left of the critical point in Figure 14a is, of course, also determined by the torque versus control current curve shown in Figure 14b. The difference between the torque obtained from increasing and decreasing control current is shown in Figure 2.

Use of the term *slip torque*, incidentally, is to emphasize that the torque acts between two mechanical parts which may be moving relative to one another because these brakes may be used as tension control devices as well as a means of stopping the rotation entirely.

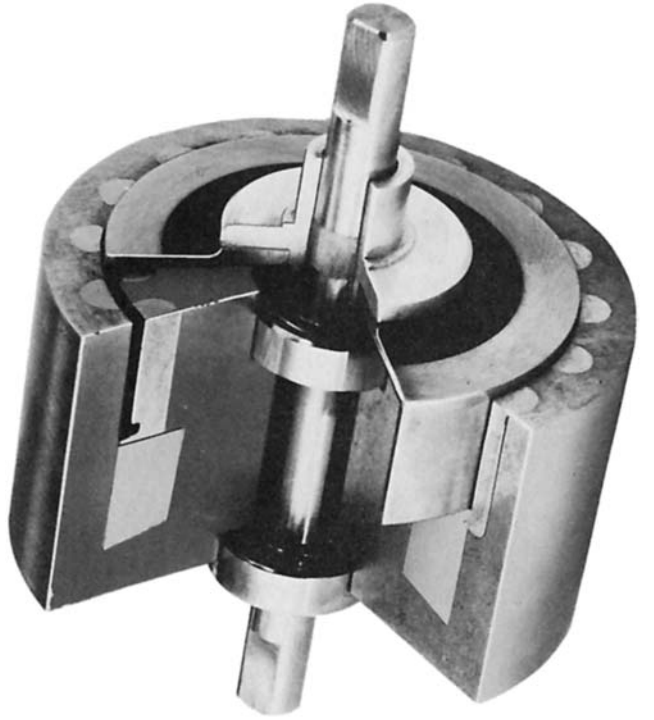

FIGURE 10 Hysteresis clutch with cutout section showing the OM (which also forms the outer shell), the IM, and the electromagnetic coil. (Courtesy of Magnetrol Inc., Buffalo, NY.)

IV. EDDY-CURRENT BRAKES AND CLUTCHES

Construction of eddy-current brakes is physically similar to that of hysteresis brakes. The essential difference is that the IM is now made of a magnetically soft material (one having large μ, a small magnetization vector M, and therefore, easy magnetization) which also has a low specific resistance. Although there are small hysteresis losses in eddy-current clutches and brakes, just as there are small eddy-current losses in hysteresis clutches and brakes, the primary source of power loss in these brakes is in the generation of eddy

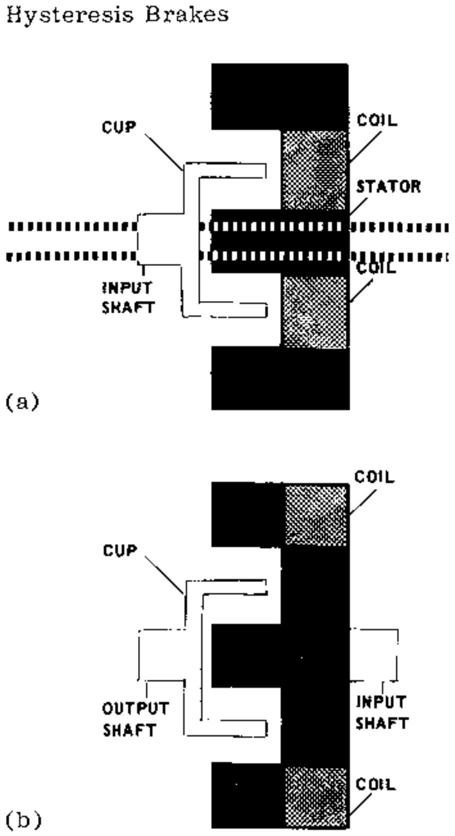

FIGURE 11 Schematic of (a) a hysteresis brake and (b) a hysteresis clutch. The E-shaped cross section represents the cross section of the OM and its inner post (the outer shell in Figure 10). (Courtesy of Magnetrol, Inc., Buffalo, NY.)

currents in the IM. These eddy currents, which are often represented as small current loops, as illustrated in Figure 15, are generated in a direction to oppose the change in the magnetic field whenever there is a change in the magnetic field crossing the IM. Pole geometry for an eddy-current brake/clutch is shown in Figure 12 where the outer ring a is the cup, or OM, and the inner cylinder a is the central post (Figure 11), which completes the magnetic circuit, and the intermediate ring b is the IM, which rotates in the magnetic field between the cup and the inner post. The rate of change of the magnetic field due to relative rotation between the IM and the OM is

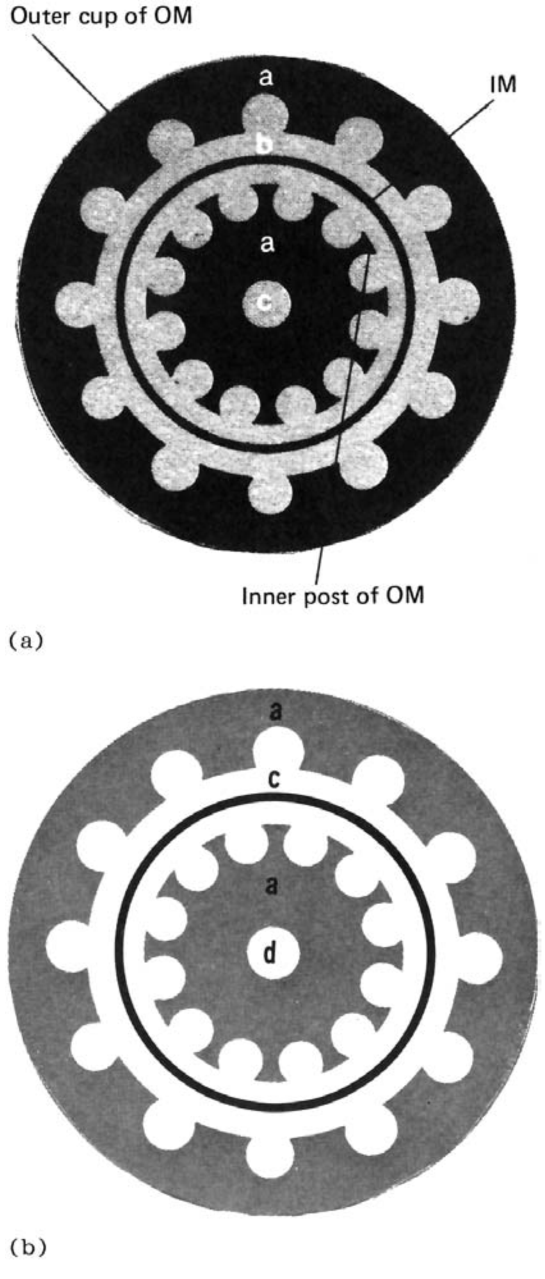

FIGURE 12 Schematic of a cross section of a hysteresis brake in a plane perpendicular to the shaft axis-showing reticulation of the OM cup walls and inner post. (Courtesy of Magnetrol, Inc., Buffalo, NY.)

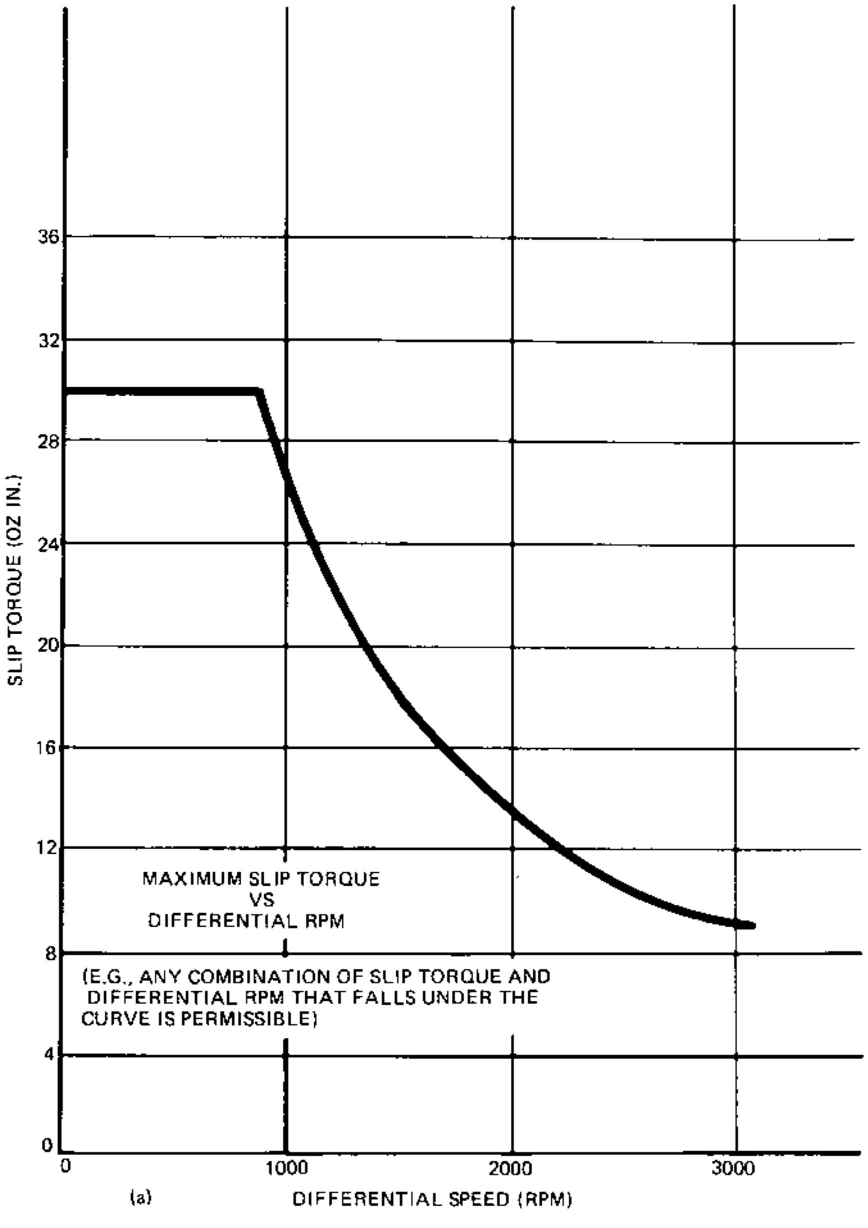

Figure 13 Torque (also termed slip torque) differential speed (or slip speed) for hysteresis brakes of different capacity. The dashed line shows the effect of increased cooling. (Courtesy of General Electro-Mechanical Corp., Buffalo, NY.)

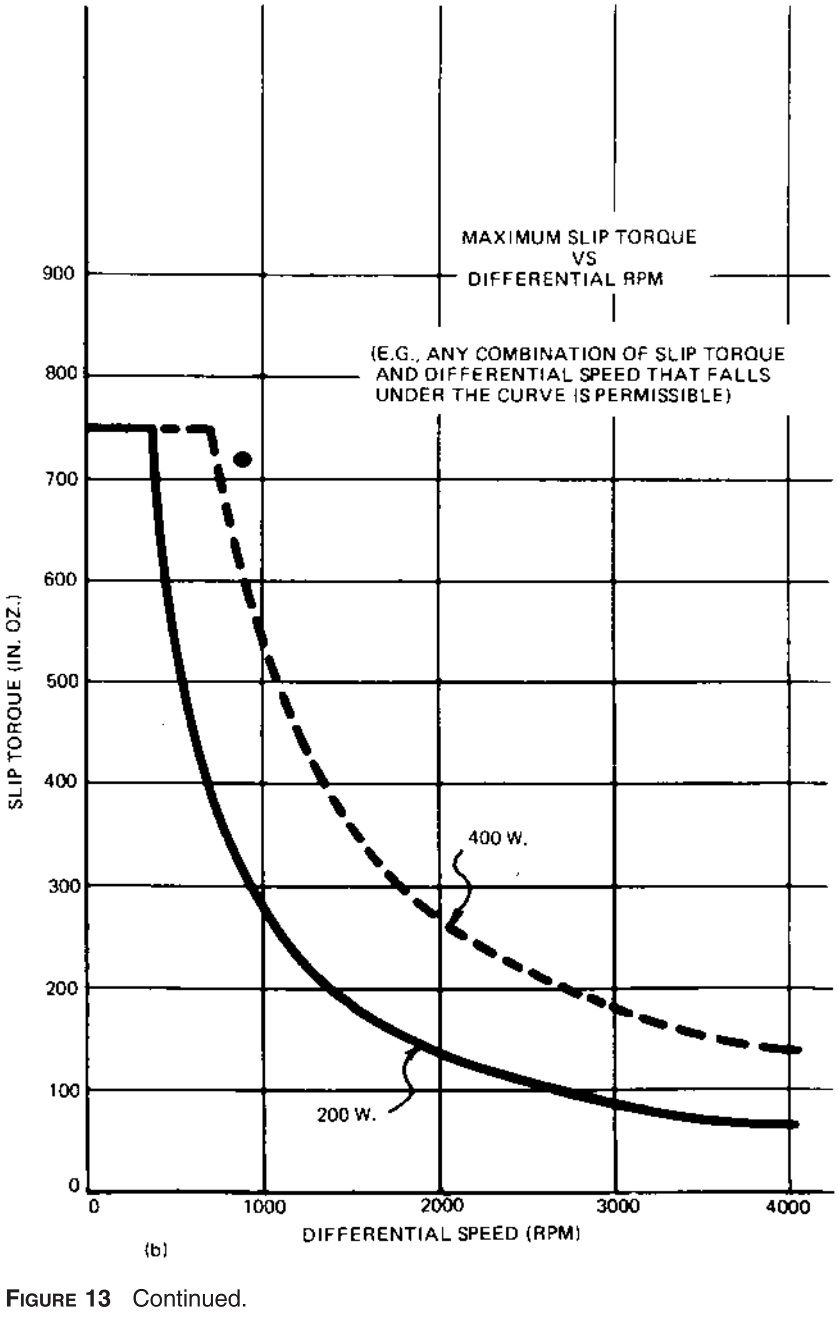

FIGURE 13 Continued.

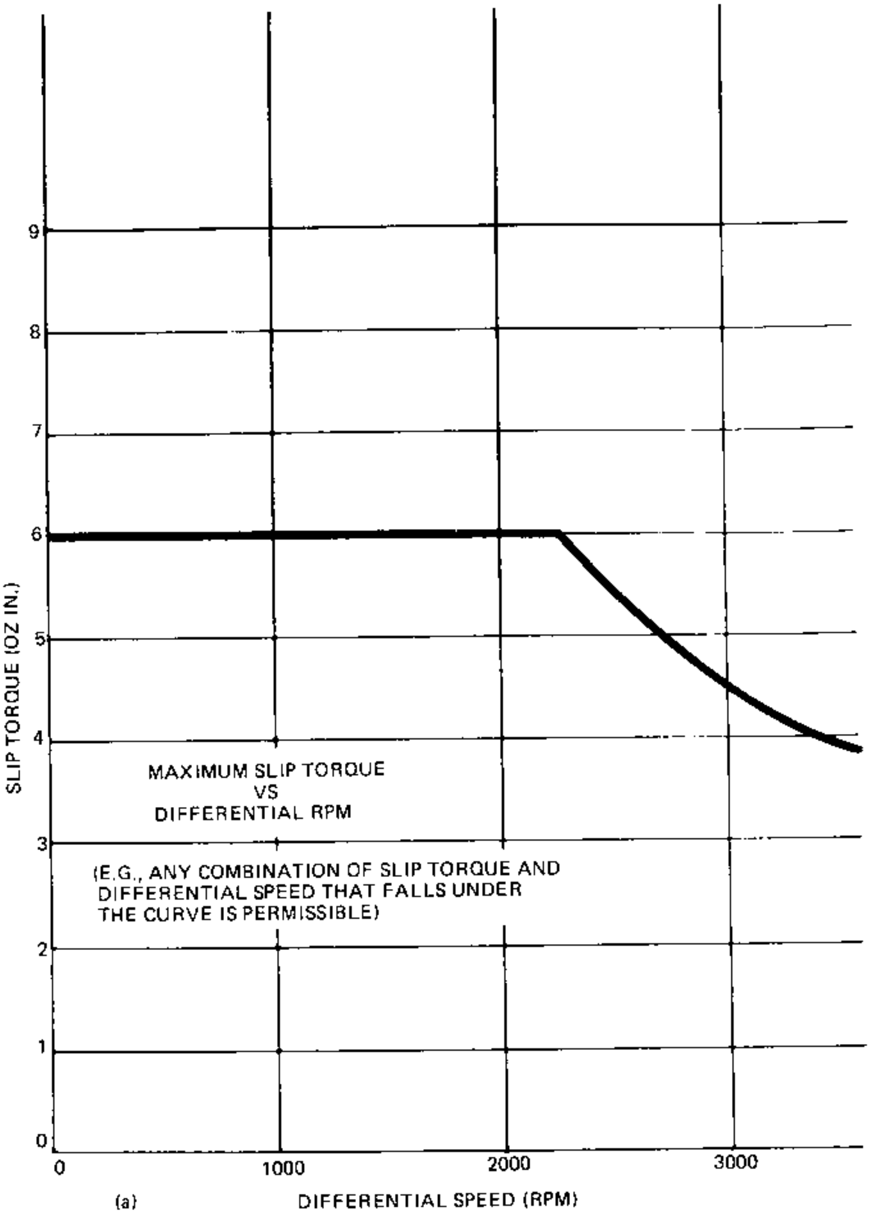

FIGURE 14 Torque versus differential speed (a) and torque versus control current (b) for a particular hysteresis brake. Torque differential speed curve shown corresponds to approximately 30 mA of control current through a 1900-Ω coil. (Courtesy of General Electro Mechanical Corp., Buffalo, NY.)

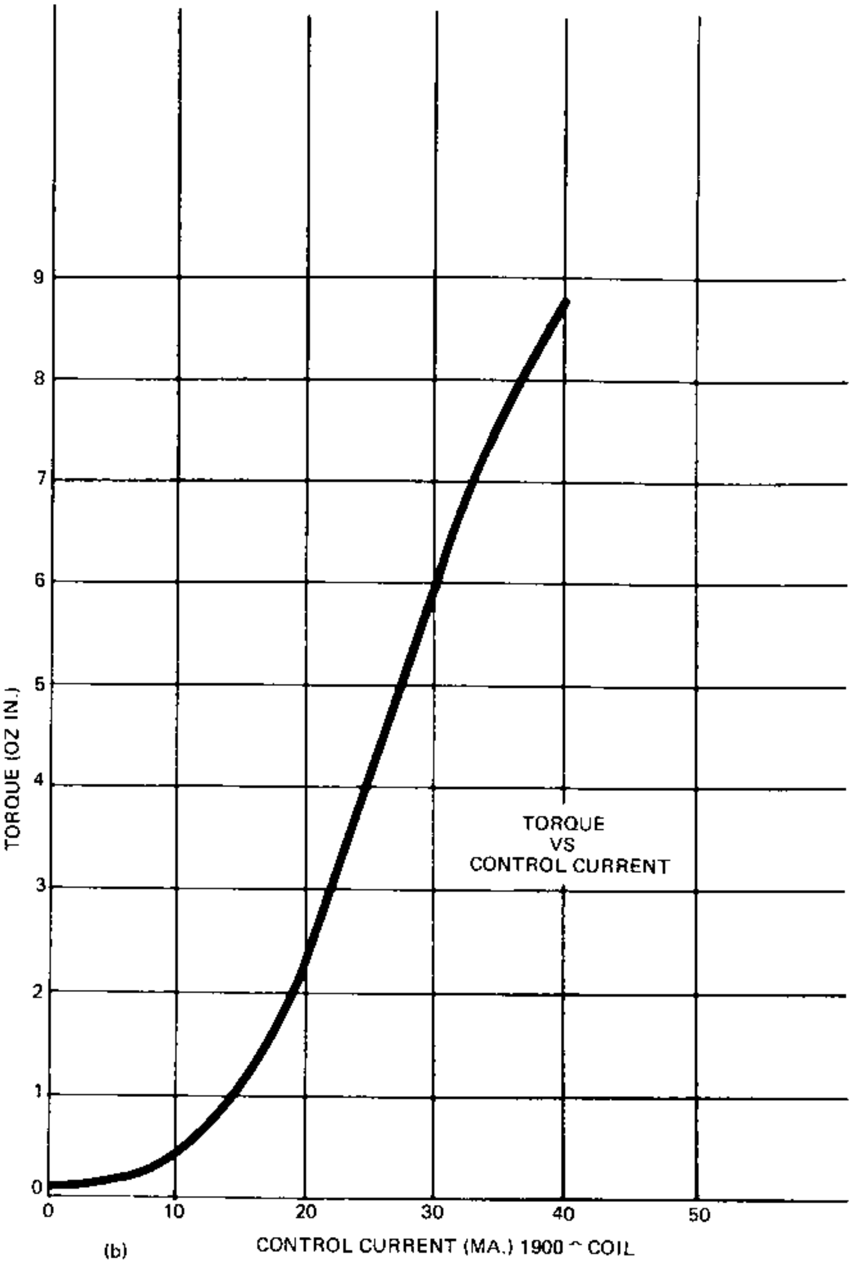

FIGURE 14 Continued.

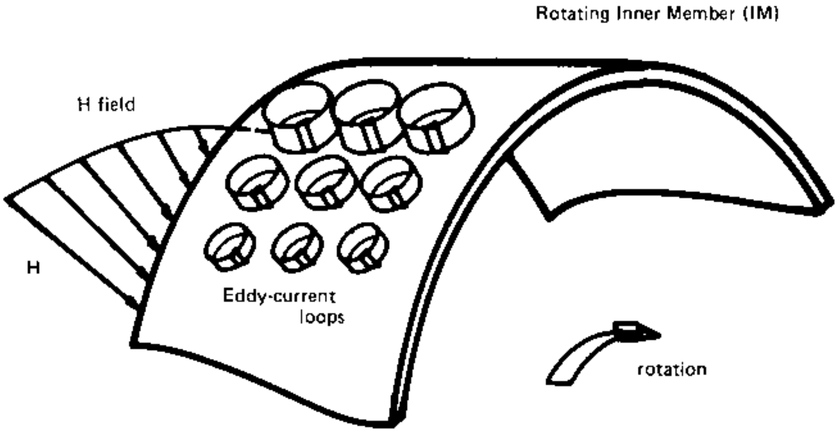

FIGURE 15 Eddy-current loops induced in the IM by the changing **H** field in an eddy-current brake.

determined by the number of poles in the OM and the rotational speed of the IM. From the frequency term f in equation (1-11) we see that the power dissipated is, therefore, proportional to the number of poles and the rotational speed. Although the braking torque is zero at 0 rpm, it does not increase linearly with the rotational speed for speeds at the upper end of the operating range because of effects not explicitly shown in equation (1-11), as demonstrated by the torque versus rotational speed curves shown in Figure 16. Notice that the torque maxima in these curves are directly related to the percent excitation, so that they provide current versus torque data as well.

Figure 17 illustrates a model of air-cooled eddy-current brakes produced in sizes having heat dissipation capacities from 5 to 100 hp and braking torque capacity from 60 to about 1800 lb-ft. Larger eddy-current brakes with dissipation capacities up to 4000 hp are liquid cooled, while smaller brakes, with capacities of several ounce-inches, require no cooling other than local convection air currents.

These brakes are used in applications where tension is to be maintained either by preventing a shaft from overspeeding due to external torque or by controlling tension between two sets of roller by having one set rotate opposite the direction of applied torque, thus stretching the material between these two sets of rollers. Small torque models are used for controlling tension in filiment manufacture and in magnetic tape drives, while the larger models find applications in laying cables, winding sheet metal rolls, and in conveyor controls.

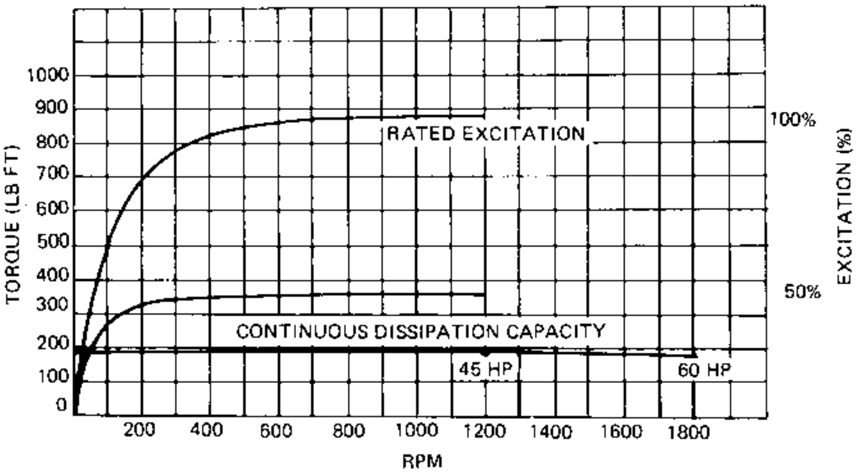

FIGURE 16 Combined torque rotational speed curve and torque excitation curves for eddy-current brakes. (Courtesy of Eaton Power Transmission Systems, Industrial Drives Operations, Kenosha, WI.)

Simplatrol Dana produces a small-capacity (under 8 oz-in.) unit designed to have an adjustable torque range and to use the construction similarities between eddy-current and hysteresis brakes/clutches. In it the IM and OM are replaced by a permanent-magnet disk and either an eddy-current or hysteresis disk. Torque capacity may be adjusted by means of the flux gate placed between them, as shown in the brake version in Figure 18. Manual rotation of the flux gate relative to the magnetic disk determines the strength of the magnetic field that acts on either the hysteresis or eddy-current disk attached to the front, unthreaded, shaft on the assembly shown. The rear disk, the magnetic plate, and the flux gate rotate together in the case of a clutch, or remain stationary in the case of a brake. Clutch and brake units differ only in that the rear shaft of the brake is threaded, as shown in the figure.

The torque versus speed curves for an eddy-current brake in Figure 16 may also be used to deduce the characteristics of an eddy-current clutch; namely, that an eddy-current clutch can provide a controlled soft start between a driver and a driven unit by controlling the excitation current as a function of the speed difference. Likewise, an eddy-current clutch may also be considered when a driven machine may experience speed changes of several hundred rpm that should not impose a large torque change on driving machine. Since the torque available to accelerate a driven machine back up to speed will be small, an eddy-current clutch will be suitable only if prolonged

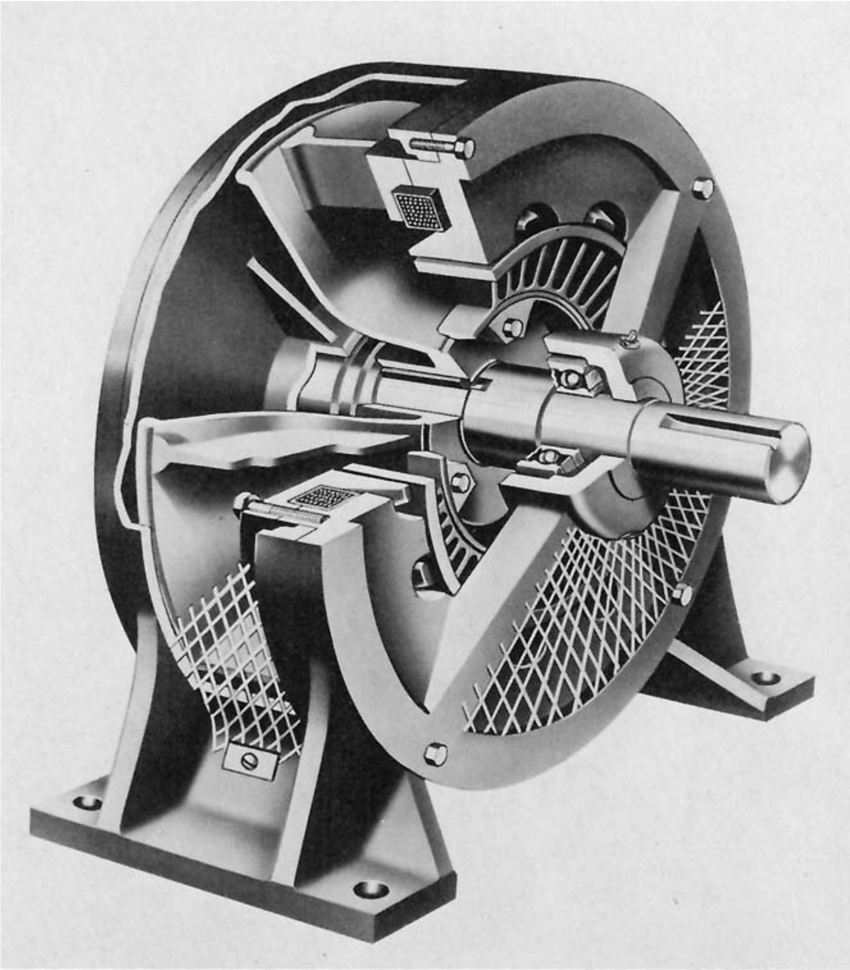

Figure 17 Air-cooled eddy-current brakes with torque capacities from 5 to 1740 lb-ft and power dissipation from 0.75 to 100 hp. (Courtesy of Eaton Power Transmission Systems, Industrial Drives Operations, Kenosha, WI.)

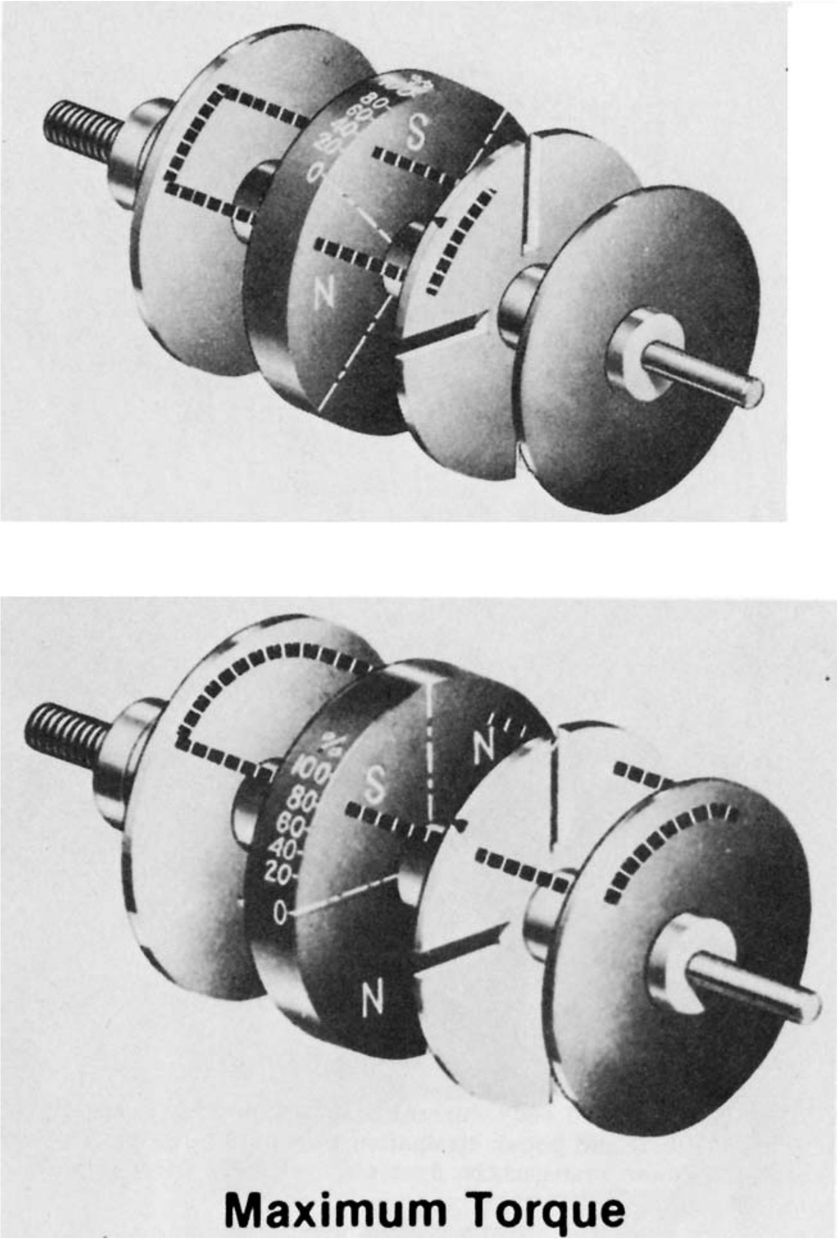

Figure 18 Combination hysteresis/eddy-current brake/clutch. (Courtesy of Simpatrol Dana Industrial, Webster, MA.)

periods of speed deviation are acceptable. Eddy-current clutches and brakes may, for example, be used in tape recorders to provide both a soft start to the tape drive and a gentle, programmed, control of the tape speed and to prevent over-speeding of the supply reel.

V. NOTATION

$\mathbf{B}$	magnetic induction
$\mathbf{D}$	electric displacement
$\mathbf{E}$	electric field intensity
f	frequency
$\mathbf{H}$	magnetic field intensity
I	current
$\mathbf{J}$	current density
k	specific resistance of a material
$\mathbf{M}$	magnetization vector
N	number of turns
$\boldsymbol{n}$	unit vector normal to surface S
$\mathbf{P}$	polarization vector
P_e	power loss due to eddy currents
S	surface
t	time
V	volume
W	work
x,y,z	spatial coordinates
δ	plate thickness
ε	electric permeability
μ	magnetic permeability
ρ	charge density

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2. Lammeraner, J., Stafl, M. (1996). English translation. In: Toombs, G. A., ed. *Eddy Currents*. London: Iliffe Books, Ltd.