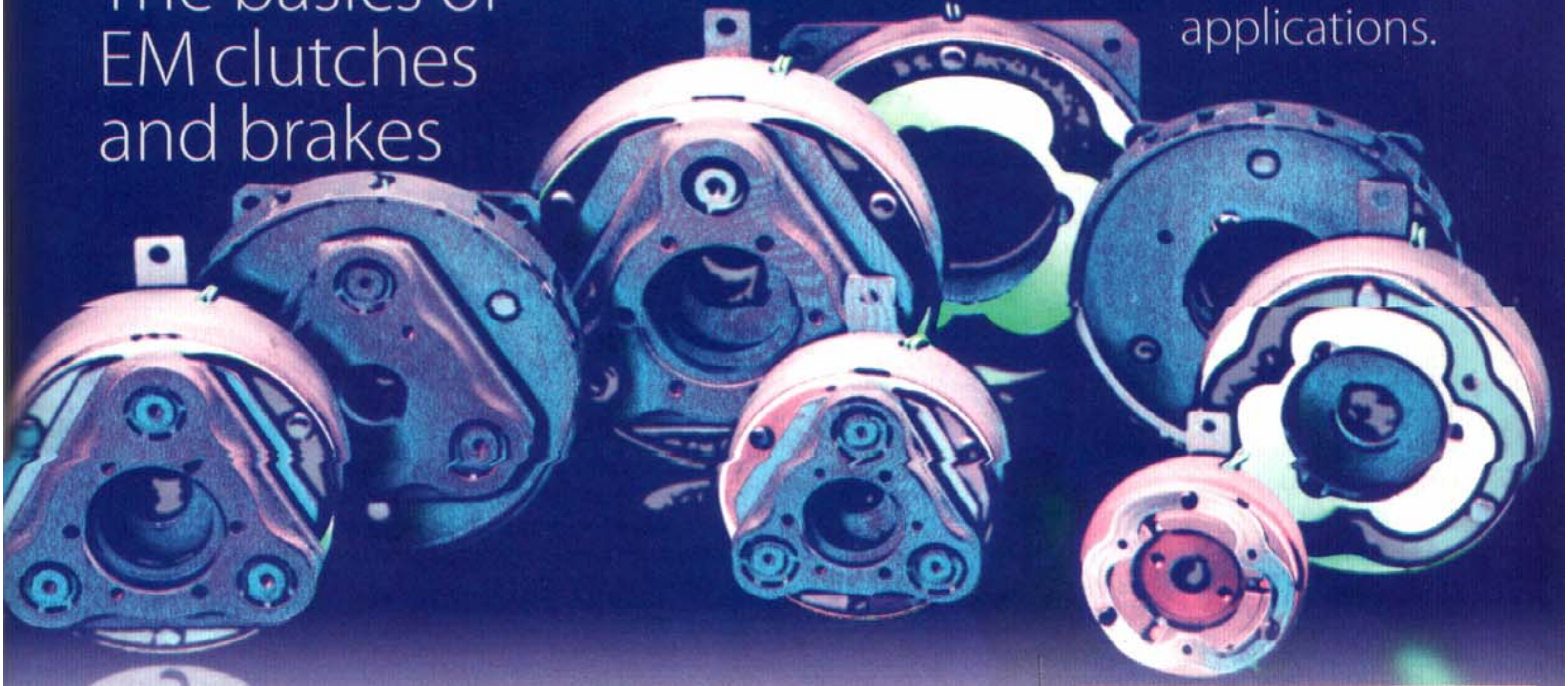
Friction and **magnetism**

The basics of EM clutches and brakes

Electromagnetic clutches and brakes seem simple, but complex variations fit them to multiple applications.



People use electromagnetic (EM) clutches and brakes every day and often don't realize it. Anyone who switches on a lawn tractor, copy machine, or car air conditioner may be using an EM clutch — and EM brakes are just as common.

Electromagnetic clutches operate electrically but transmit torque mechanically. Engineers once referred to them as electromechanical clutches. Over the years EM came to stand for electromagnetic, referring to the way the units actuate, but their basic operation has not changed.

Electromagnetic clutches and brakes come in many forms, including tooth, multiple disc, hysteresis, and magnetic particle. However, the most widely used version is the single-face design.

Elements of EM

Both EM clutches and brakes share basic structural components: a coil in a shell, also referred to as a field; a hub; and an armature. A clutch also has a rotor, which connects to the moving part of the machine, such as a driveshaft.

The coil shell is usually carbon steel, which combines strength with magnetic properties. Copper wire forms the coil, although sometimes aluminum is used. A bobbin or epoxy adhesive holds the coil in the shell.

Activating the unit's electric circuit energizes the coil. The current running through the coil generates a magnetic field. When magnetic flux overcomes the air gap between the armature and field, magnetic attraction pulls the armature — which connects to the hub — into contact with the rotor.

Magnetic and friction forces accelerate the armature and hub to match rotor speed. The rotor and armature slip past each other for the first 0.02 to 1.0 sec until the input and output speeds are the same. The matching of speeds is sometimes called 100% lockup.

Brakes lack a rotor, so magnetic flux acts directly between the armature and

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Key points:

- Electromagnetic clutches and brakes are electrically activated but transmit torque mechanically.
- Engagement time depends on magnetic field strength, air gap, and inertia.
- Burnishing increases initial clutch or brake torque, and overexcitation cuts response time.

Resources:

www.inertia-calc.com

Ogura Industrial Corp., *www.ogura-clutch.com*

"Getting a grip on clutch and brake selection," MACHINE DESIGN, Sept. 9, 1999, *machinedesign.com/article/getting-a-grip-on-clutch-and-brake-selection-0909* field. The field usually bolts to the machine frame or on a torque arm that handles brake torque. When the armature contacts the field, braking torque transfers into the field housing and machine frame, decelerating the load. As in a clutch, speed can change quickly.

Most industrial applications use single-flux, two-pole clutches. These have one north-south flux path between the rotor and armature. However, mobile clutches and other specialty electromagnetic clutches can use a double or triple-flux rotor. These clutches have slots in both the rotor and armature that create additional air gaps between the two parts. These curved slots run parallel to the rotor or armature circumference, so they are often called banana slots.

Taking the path of least resistance, magnetic flux weaves between the rotor and armature two or three times when the faces engage. This weaving produces multiple north-south pole pairs. Each pair can increase the torque in a clutch.

In theory, an additional set of poles at the same diameter as the first set would double the operating torque. In practice, however, each addition shrinks the diameter of all contact points. The serpentine path the magnetic flux takes also diminishes the available flux. But a double-flux design pushes up torque 30 to 50%, and a triple-flux design can bring a 40 to 90% torque boost over a single-flux unit.

The ability to increase torque without a heavier or larger clutch is especially important in weight-sensitive applications. Alternately, engineers may be able to specify smaller clutches to get the required torque.

For both clutches and brakes, turning off the power to the coil disengages the unit. As soon as power is cut, flux falls rapidly and the armature separates. One or more springs help push the armature away from its contact surface and maintain a predetermined air gap.

All torqued up

So how much torque will a given brake or clutch supply? The main factor affecting the torque rating of a clutch or brake is the combination of voltage and current. The fields of EM clutches and brakes can be constructed for almost any dc voltage. The torque the unit produces will be the same as long as it is supplied with the correct operating voltage and current.

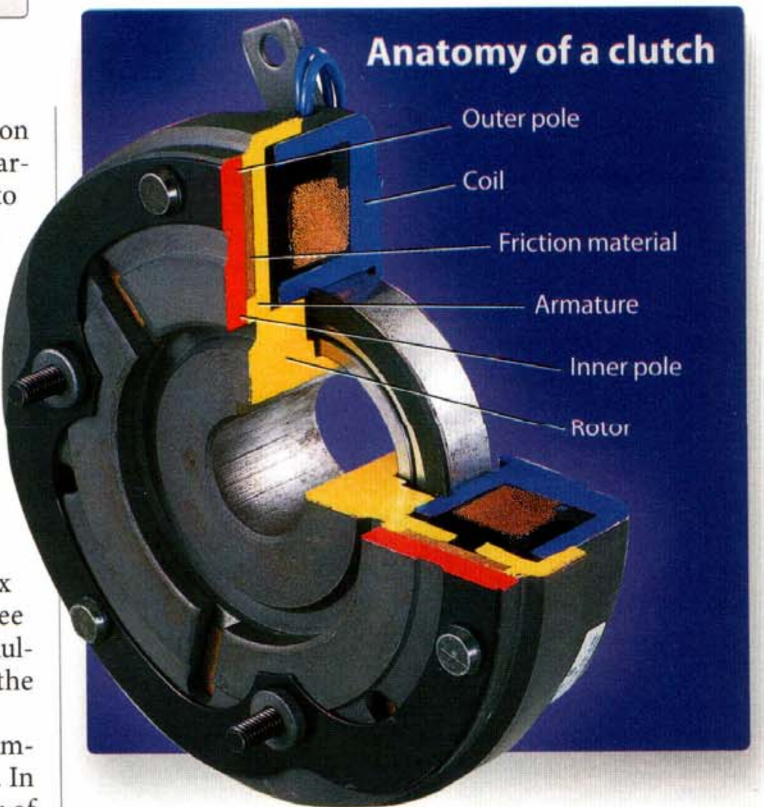
Electrical current controls the change in magnetic field strength, dB, as shown by:

$$dB = (\mu_0 I/4\pi) \times dl \sin(u)/r^2$$

where I = net current, r = displacement vector from the coil to the point at which we want to know the magnetic field, u = angle between the vector and a current element dl, and μ_0 = magnetic moment of the dipole.

For instance, a 90-V clutch, a 48-V clutch, and a 24-V clutch, all powered with their respective voltages and constant current, would each produce the same amount of torque. However, applying 48 V to a 90-V clutch results in about half the torque output. This is because voltage and torque have a nearly linear relationship.

Because voltage and current are so important for maximum torque output, designers specify constant-current power supplies for critical applications. Less-expensive rectified power supplies keep voltage constant but let current change as resistance changes. Based on $V = I \times R$, available current falls as resistance increases. An increase in resistance often results from rising temperature as the coil heats up, according to:



In an EM clutch, current running through the coil generates a magnetic field that attracts the armature toward the rotor. The rotor connects via a hub to the rotating input, like a driveshaft, while the armature connects to the output. Contact transfers torque between the armature and rotor, bringing the output up to the input speed.

$$R_f = R_i \times [1 + \alpha_{Cu} \times (T_f - T_i)]$$

where R_f = final resistance; R_i = initial resistance; α_{Cu} = 0.0039°C^{-1}, copper wire's temperature coefficient of resistance, ; T_f = final temperature; and T_i = initial temperature.

Because magnetic flux degrades with elevated coil temperature, torque declines by about 8% for every additional 20°C in the coil. Designers can compensate for minor temperature fluctuations by slightly oversizing the clutch or brake, with the advantage of being able to use a less-expensive rectified power supply instead of a constant-current source.

Designers must also distinguish between the clutch or brake's dynamic and static-torque ratings. Applications with relatively low rotational speed — 5 to 50 rpm depending upon the unit's size — need not consider dynamic torque. The static torque rating is usually closest to the application's conditions.

However, a designer specifying a clutch or brake for a machine that runs at 3,000 rpm must determine the unit's dynamic torque. Almost all manufacturers list products by static-torque rating, but dynamic torque can be less than half the static rating. Most manufacturers publish torque curves showing the relationship between dynamic and static torque for a given series of clutch or brake. (A sample curve is shown in the accompanying graphic.)

Timely torque

Torque is probably the designer's first consideration when specifying EM clutches or brakes, but engagement time is important, too. There are actually two engagement times to consider. The first is the time it takes the coil to develop a magnetic field strong enough to pull in the armature. The second, the time-to-speed or time-to-stop for clutches and brakes, respectively, relates to the unit's inertia.

Inertia depends on the mass and geometry of the rotating system. Web sites like *inertia-calc.com* can help designers determine a system's inertia and the torque needed to accelerate or decelerate that load in a given time.

Most CAD systems can calculate component inertia, but the key to sizing clutches is calculating how much inertia is reflected back to the clutch or brake. To do this, engineers use the formula:

$$T = (WK^2 \times \Delta N) / (308 \times t)$$

where T = required torque (lb-ft), WK^2 = total inertia (lb-ft^2), ΔN = change in the rotational speed (rpm), and t = time during which the acceleration or deceleration must take place. The inertia term accounts for rotating component's weights, W (lb) and the radius of gyration (ft), K. Designers sizing a clutch or brake must first determine this inertia to calculate how much torque the unit can handle.

Compared to inertial considerations, the time needed to develop a sufficient magnetic field to actuate the brake or clutch is short.

Magnetic-field strength depends on the number of turns in the coil. The air gap between the armature and clutch rotor or brake face is a resistance the magnetic field must overcome. Magnetic lines of flux diminish quickly in air, so the greater the gap, the longer it takes the armature to develop enough magnetic attraction.

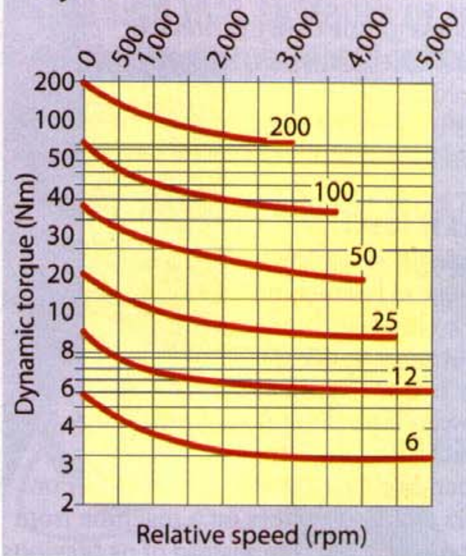
High-cycle applications often use floating armatures that rest against the rotor or brake face, making the air gap zero and response time consistent.

In fixed-armature designs, engineers must consider the air gap in new units as well as the gap in the future as contact surfaces wear and the gap grows. In high-cycle applications where accuracy is important, even a difference of 10 to 15 msec can affect performance. And in normal-cycle applications, a new machine with accurate timing can eventually see a "drift" in accuracy due to wear.

Consider a cut-to-length application where a photo-eye reads a mark on the material to determine where to stop the material flow and make a cut. If the machine is not calibrated accordingly, it will produce slightly longer pieces over time than when it was brand new because wear widens the air gap, creating a slightly longer pull-in time.

To speed responses, some EM clutches and brakes use overexcitation. The unit's power supply gives the coil a burst of voltage significantly higher than its nominal rating for a few milliseconds. Higher voltage lets the coil generate a more-powerful magnetic field more quickly, starting the process of attracting the armature and accelerating or decelerating the load.

Dynamic determination



Designers can use manufacturer-generated curves to determine dynamic torque at a given rpm from a clutch or brake's static torque rating. Each curve represents a different static rating.

Three times the rated voltage typically gives around one-third faster response. Overexcitation of 15 times the normal coil voltage produces responses three times faster. For instance, a clutch coil rated for 6 V should be overexcited to 90 V to cut response time to one-third of the original.

Once overexcitation is no longer needed, the power supply returns to its normal operating voltage. Overexcitation can be repeated as needed, but the high-voltage bursts must be short enough that they do not overheat the coil.

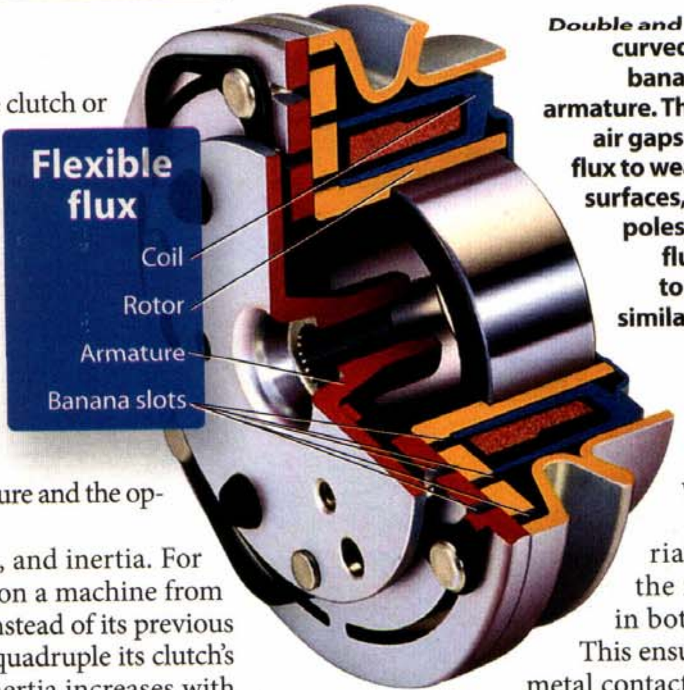
The benefits of burnishing

Although armatures, rotors, and brake faces are machined or even lapped as flat as possible at manufacture, peaks and valleys remain on the surfaces. When a new clutch or brake engages, the contact area is initially confined to the peaks on the mating surfaces. This smaller contact area means torque can be as much as 50% less than the unit's static torque rating.

To get the full torque, users need to burnish mating surfaces. Burnishing cycles the unit, letting those initial peaks wear down so there is more surface contact between the mating faces. These cycles — 20 to over 100 of them, depending on the amount of torque required — should be lower in inertia, speed, or both, than the end application.

For some designs, like bearing-mounted clutches with the rotor and armature connected and held in place by a bearing, users can complete the burnishing on a bench top or burnishing station instead of on the machine. On the other hand, two-piece clutches or brakes, which have separate armatures, burnish better after installation. That's because armature alignment and, hence, burnishing lines can shift slightly when the unit moves.

Such alignment shifts may produce small torque reductions that would only be noticed in torque-sensitive applications. Other applications may not need burnishing at all.



Double and triple-flux clutches have curved slots, sometimes called banana slots, in the rotor and armature. The slots create additional air gaps that cause the magnetic flux to weave between the contact surfaces, boosting the number of poles and the torque. A triple-flux clutch can transmit up to 90% more torque than a similarly sized single-flux unit.

If the system needs less torque than the clutch or brake provides out of the box, users can skip the burnishing step. In general, burnishing is more critical on higher torque devices.

How long does it last?

Normal operations wear down contact surfaces, just as burnishing does. Every time a clutch or brake engages during rotation, a certain amount of energy is transferred as heat. This transfer wears both the armature and the opposing contact surface.

Wear rates depend on size, speed, and inertia. For example, if workers changed pulleys on a machine from 1:1 to 2:1 so that it ran at 1,000 rpm instead of its previous speed of 500 rpm, the change would quadruple its clutch's wear rate. That's because reflected inertia increases with the square of the speed ratio. That is:

$$(WK^2)r = WK^2 \times \Delta N^2.$$

In such situations, a fixed armature stops engaging when the air gap gets too large for the magnetic field to overcome. Zero-gap or auto-wear armatures can wear to less than one-half of their original thickness before failing.

Designers can estimate life from the energy transferred each time the brake or clutch engages.

$$E_e = [m \times v^2 \times \tau_d]/[182 \times (\tau_d + \tau_l)]$$

where E_e = energy per engagement, m = inertia, v = speed, τ_d = dynamic torque, and τ_l = load torque. Knowing the energy per engagement lets designers calculate the number of engagement cycles the clutch or brake will last:

$$L = V/(E_e \times w)$$

where L = unit life in number of cycles, V = total engagement area, and w = wear rate.

Clutches subject to low speed, low side loads, or infrequent operation often use bushings on rotating parts. Although less expensive than bearings, bushings tend to fail before the air gap grows to the point of failure. At higher loads and speeds, bearing-mounted fields, rotors, and hubs are better options. Unless bearings are stressed beyond their physical limitations or become contaminated, they tend to have a long life and are usually the next area to fail after the air gap.

It is rare for a coil to stop working in an EM clutch or brake. Coil failures are usually due to heat-induced breakdown of the coil-wire's insulation. Causes include high ambient temperature, high cycle rates, excessive slipping between the armature and contact surface, and the application of higher voltage than the coil rating permits.

Figuring on friction

The torque between an armature and clutch rotor or brake field is derived from the steel-to-steel coefficient of friction and magnetic force, but most industrial designs add friction material to change torque or wear characteristics.

The friction material is recessed between the inner and outer poles in both brakes and clutches. This ensures magnetic metal-to-metal contact between the armature and coil shell or rotor but expands the contact surface area. The larger area slows wear and extends cycle life. In some applications, materials such as ceramics have greatly extended life in clutches and brakes to 25 or 50 million cycles.

Clutches in automobiles, agricultural equipment, and construction gear tend not to use friction material because they have lower cycle requirements than industrial clutches. In addition, mobile equipment is often exposed to wet weather that can swell friction materials and cut available torque.

While most friction materials primarily slow wear, they can also be used to alter the relatively high coefficient of friction of steel-to-steel contact. An engineer who needs a clutch or brake with extended slip time might specify a material with a lower coefficient of friction. Conversely, for slightly higher torque, common in low-rpm applications, desingers might use high-coefficient-of-friction materials such as cork.

No matter what material designers choose, the wearing action creates particulates. Where particulates are problematic, such as in clean-room and food-handling applications, units should be enclosed to keep particles from contaminating the surroundings.

However, a more-common scenario is that the clutch or brake becomes contaminated by something in the environment. Oil or grease should be kept away from clutches or brakes because they reduce friction between contact surfaces, lowering available torque. The same is true for oil mists and airborne lubricant particles in the work area.

Dust and other contaminants that fall between contact surfaces can also reduce torque. Designers who know their clutch or brake will be in a contaminant-prone environment may choose to add a shield to protect contact surfaces.

Clutches and brakes that have not been used in a while can rust on the contact surfaces. This is generally not a major concern because the rust wears away within a few cycles, leaving no lasting impact on torque. **MD**