MOTOR DESIGN ADVANCEMENTS

USING NdFeB MAGNETS

I. INTRODUCTION:

Electric motors with permanent magnets have seen a significant rise in market share and are being used in an increasingly wide range of applications. The availability of these magnets has played a major role in this growth. The advent of neodymium iron magnets and the improvements in their manufacturing in the last decade have dramatically impacted these motors. The parameters which are directly affected by these magnets are reviewed to further the understanding of their role in the industry. The record of annual sales of this type of magnet speaks for itself.

The reasons for this success lie partially in the lower cost of the material, but mainly in its being coupled with the higher energy-products being achieved. This paper will only discuss how the magnet characteristics benefit the motor performance.

II. MATERIAL CHARACTERISTICS:

One magnet material from one supplier is chosen to identify the parameters which are relevant to the motor design and performance. This is NEOMAX-R32H from SUMITOMO SPECIAL METALS CO., Ltd. with the following characteristics:

B_r = 11.5 kG at 23°C

H_c = 10.8 kOe

$(BH)_{max}$ = 31.3 MGOe

H_{ci} = 18.8 kOe

recoil permeability = 1.05

temperature coefficient of B_r = - 0.12 %/°C

temperature coefficient of H_{ci} = - 0.58 %/°C

density = 7.4 gm/cm3

electrical resistivity = 144 micro ohm cm

coefficient of thermal expansion = 5.8 E-6/°C (parallel) coefficient of thermal expansion = - 1.3 E-6/℃ (perpendicular)

The demagnetization characteristics shown in Figure 1 are typical of magnets of this family. The generally linear BH characteristics are not unusual for these materials at temperatures below about 100°C (Ref. 1). Operation is still acceptable up to 150°C despite some non-linearity in the curves, and up to 180°C in more recent materials (Ref. 2).

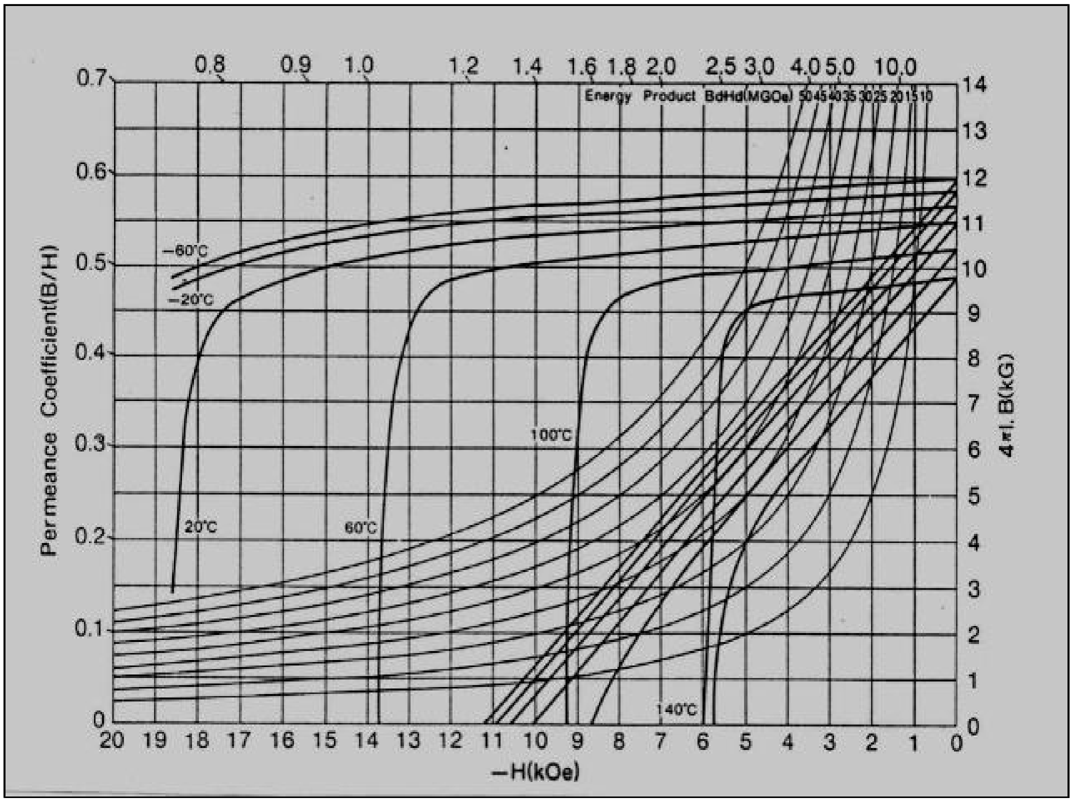


Figure 1: Demagnetizing characteristics NEOMAX-32H

III. MOTOR DESIGNS:

The choice of magnet material is one of the first exercises done when designing an electric motor. The issues most relevant are:

A. Remanent flux density B_r

B. Coercive force H_c

C. Energy product $(BH)_{max}$

D. Temperature coefficients

E. Magnetizing force

F. Curie temperature

G. Thermal expansion

H. Volume & weight

I. Cost

J. Other features

These issues are not arranged in any order of priority since that is determined by what is best for the specific application. There are also other issues relevant to the design which are usually of secondary importance. These are issues with effects on the performance, which can be tolerated while the main objectives of the design are met. Following is a discussion of the issues listed above:

A. Remanent flux-density B_r:

This value is the intercept of the demagnetization characteristics with the y-axis (Figure 1). It is the value of the flux-density at the surface of the magnet when it is surrounded by a magnetically perfect medium. This, of course is never the case in any magnetic device but it is still a useful parameter in the design process when a comparison between materials is made. The actual value at which the device ultimately operates is lower than B_r by varying amounts, depending on the operating point on the demagnetization characteristics. In the case of electrical motors, the operating point depends primarily on the type and condition of the steel around the magnet and the width of the air-gap separating the rotor and stator. To operate at the highest possible point, the air-gap width is reduced as much as possible and the best magnetic material used. However, it is very desirable to use a high B_r magnet even with the above design features optimized. The reason being the desire to maximize the air-gap flux-density (B_g) of the motor. In permanent magnet motors, B_g is directly related to the amount of torque the motor is capable of producing,

$$T_{cont}\ \alpha\ B_g \qquad (1)$$

Hence, the high value of B_g achievable with NdFeB magnets has rendered this material very attractive and made it possible to increase the torque of motors without substantially altering their size. While it is true that an increase in Bg results in a corresponding increase in torque, the relationship is not linear between B_r and torque. The reason being the non-linearity of the magnetic circuit which must carry the flux (Ref. 10). But the benefits of having access to a high B_r material exceed the gains from optimizing the motor design.

B. Coercive force H_c*:*

Figure 1 shows the coercive force as the intercept of the demagnetization characteristics and the x-axis. This value is the amount of the external magnetic field needed to totally demagnetize the magnet and bring the value of B_r to zero.

Naturally the higher H_c gets, the more difficult it is to demagnetize the magnet totally. This makes a magnet material like NdFeB, which has a high H_c, very resistant to the demagnetizing effects of external fields such as those produced by short circuit currents or even starting currents in motors.

C. Energy-product $(BH)_{max}$*:*

This parameter is arrived at by multiplying the B value by the H value for each operating point along the demagnetization characteristics and selecting the maximum value of that product. Since most magnet materials have characteristics similar in shape to those of Figure 1, i.e. approximately a 45° slope, a high energy-product value can be interpreted as high values of B_r & H_c. Materials with characteristics which are either non-linear or which have other slopes would be exempt from this generalization. Nevertheless, some conclusions can be associated with this parameter when using rare earth and ferrite magnets which constitute the bulk of usage in motors.

It was determined (Ref.3) that the flux/pole increases as the square root of the energy-product ratio.

$$\phi_p \; \alpha \; \sqrt{(\mathrm{BH})_{\mathrm{max}}} \qquad (2)$$

Flux/pole ϕ_p affects the motor torque in a similar way to the B_r discussed above, i.e., directly. For example, the advantage of using a NdFeB magnet of 25% more $(BH)_{max}$ than other rare earth magnets is therefore 12%. For a given magnet volume, the continuous torque varies as the square of the energy-product ratio: (Ref.4).

$$T_{cont} \, \alpha \, (BH)_{max}^{2} \qquad (3)$$

It was found from comparing an induction motor with a permanent magnet synchronous motor of the same continuous torque that the induction motor was 70% more in weight and volume (Ref. 4).

When looking at the amount of magnet material needed in a particular motor, a high energy material is always preferable. It was found that the required magnet volume will vary inversely with increasing values of $(BH)_{max}$ for operation at the maximum energy-product point (Ref.5).

$$\text{Magnet volume} \, \alpha \, 1/(BH)_{max} \qquad (4)$$

Therefore, in addition to the cost saving from using less NdFeB material than other rare earth materials, the overall weight of a motor using this material is reduced. Motors with a higher power density than previously achievable become possible (2 HP/lb, Ref. 6).

D. Temperature coefficients:

Magnet materials have specific values for coefficients which describe the effect of temperature on the values of B and H in the demagnetization characteristics. The magnet specification may be given at one temperature (usually 20°C) and the designer must take into account the effect of the operating temperature range on the performance. This is done by derating the values of B and H with these coefficients. For example for NdFeB, the flux-density B drops by 0.12% for every degree C (i.e. 12% over a 100°C range), and the coercive force H drops by 0.58% for every degree C (i.e. 58% over a 100°C range). These amounts appear to be significant at high temperatures when compared with other rare earth magnets (0.04%/°C and 0.12%/°C, respectively), but can be acceptable as a result of using this magnet material. Some forms of neodymium magnets with cobalt can have coefficients as low as 0.07%/° C (Ref. 5) and would therefore, be more suited for high-temperature applications.

E. Magnetizing force:

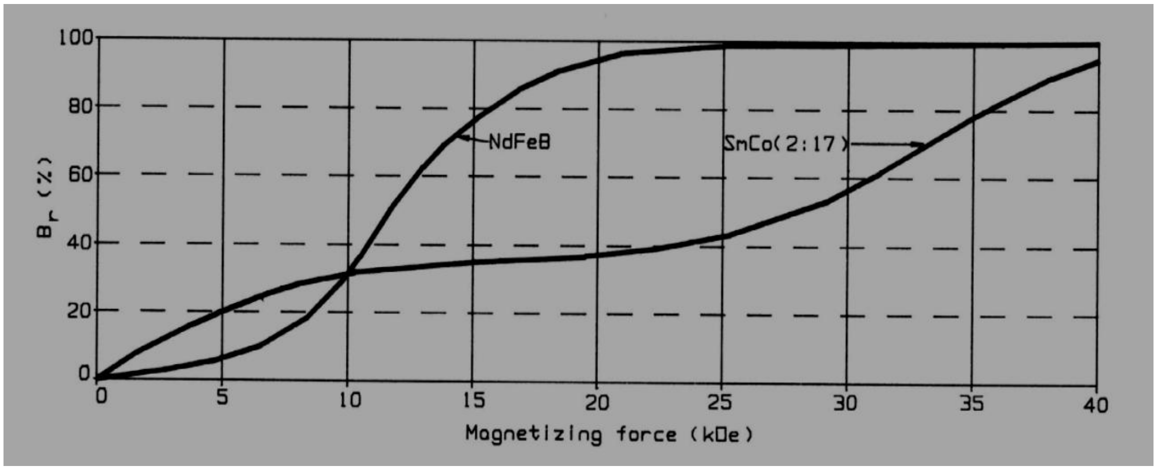


Figure 2: Magnetizing curves

The magnetizing force recommended by the magnet manufacturer is the external magnetic force which must be applied to the material to fully saturate it. The material then becomes a permanent magnet and would henceforth have an operating point on the demagnetization characteristics determined by the surrounding magnetic circuit. A magnet material does not have one particular value of magnetizing force to which reference can be made. It is rather, a range of values of magnetizing force resulting in various levels of saturation. This is shown in Figure 2 for the material being used here as an example. In certain situations, it is not possible to produce a very high force to ensure 100% magnetization, due to limited space, for example. It may still be possible to achieve a significant percentage of saturation with a moderate amount of force.

This issue is of importance when using ring magnets for small motors, where only moderate values of force can be produced when magnetizing these magnets. The NdFeB material is advantageous over other rare earth magnets since they require lower values of force to reach similar percentages of saturation. In other rare earth materials, the rate of rise in saturation is much higher than for NdFeB which narrows down the range of acceptable force. Moreover, in other rare earth materials, there could be a leveling-off of saturation over the medium range of force and a requirement for twice the force to achieve acceptable levels of saturation (Ref. 5).

This relative ease of magnetizing NdFeB magnets has opened up the field for designers to produce motors which use higher energy magnets than before. It is particularly true that the availability of these magnets has improved the performance of miniature motors through operation at higher flux-densities. Even though the amount of magnet material used per motor is small, the huge size of this market, i.e. computer peripherals, printers, other office machines, etc. is a major part of the motor industry.

F. Curie temperature:

Each magnet material has a specific temperature at which all magnetic properties are lost. This is called the Curie temperature. The operating temperature of a magnet material is well below this value and is determined primarily by how much drop in performance is acceptable compared to that at room temperature. The drop is determined with the coefficients explained in Section III.D. above.

The Curie temperature is also the temperature beyond which a permanent magnet must be heated in order to ensure full demagnetization. This process is required if the magnet needs to be remagnetized or magnetized differently from the previous state. It is extremely difficult and the results are unpredictable if a magnet is remagnetized without demagnetizing first. This is especially true of high energy magnets.

The NdFeB magnets have a Curie temperature lower than all other magnets (except Pr) and significantly lower than SmCo magnets (600° vs. 1,400°F). It is, therefore, easier to demagnetize a NdFeB magnet than other magnets with a medium temperature oven. It is, however, still necessary to conduct the demagnetization in an oxygen-free environment since all magnets contain iron which would oxidize quickly at high temperatures.

G. Thermal expansion:

NdFeB magnet materials have a coefficient of thermal expansion of about half of that of SmCo. This means that for a particular temperature range, a NdFeB magnet would experience a much smaller change in dimensions than a SmCo magnet of the same dimension. The amount of this change is important in determining the fit between the magnet and the surrounding materials. Since the surrounding material is usually steel, the design must accommodate these differences between coefficients and ensure that adequate support for the magnets is provided over the full range of temperature. The coefficient for NdFeB is about 50% of that of mild steel, whereas the coefficient for SmCo is 20% more than that of mild steel.

H. Volume and weight:

It was seen in Section III.C. above how the maximum energy-product $(BH)_{max}$ varies inversely with the required volume of the magnet. For a particular frame size, using a high energy magnet material would result in a reduction of the volume of the magnet needed. This frees up more space for other parts of the motor design and consequently, enhances the performance of the motor.

Alternatively, if the requirement is to match the performance of an existing motor, then this can be achieved with a smaller volume of magnet resulting in a smaller and lighter motor. These are substantial advantages in industries and applications where size and weight of motors is of high priority, e.g. vehicles, office equipment.

I. Cost:

There are many studies of material cost and they are constantly being updated as production methods and the markets change (Ref. 7). Information can be gathered at any time on the cost per pound of various materials, and it is well established that NdFeB falls between ferrites and other rare earth magnets. However, this is only one part of the equation when comparing magnets. The amount (volume or weight) of magnet material needed is greatly reduced when using high energy materials, as is the case with NdFeB. This has been discussed in Section III.C. and is regularly experienced by designers who are asked to balance these issues before making a selection. This is a case where engineering and economics are combined to produce the highest Watt/$ motors possible without sacrificing the Watt/lb gains made with these same materials.

J. Other features:

Since the early days of introduction of NdFeB magnets a dozen years ago (Ref. 8), it was well established that the material is relatively easy to machine compared to other rare earth magnet materials. This is due to the high iron content of these newer magnets (Ref. 1). The high iron content also results in a material of 13% less density than other rare earth magnets. That was good news in many applications. There was, however, an undesirable tendency for these magnets to get rusty with time. No application would tolerate this problem if the device using these magnets is expected to be in use beyond the onset of rust. This problem was quickly understood by the manufacturers and a lot of effort was put into resolving it with anti-rust coating. Fortunately, the material is easy to coat (Ref. 8) and before long there was a variety of coating materials and processes to choose from.

As a result of operating at higher flux-density levels when using NdFeB magnets compared to other magnets, it was found that the mechanical time constant (τ_m) of the motor is vastly improved. The relationship appears to be of the form (Ref. 9):

$$\tau_m \quad \alpha \quad J_m/B_r^{\,2} \qquad (5)$$

J_m is the moment of inertia of the motor and is determined by its rotating parts. The implications of the mechanical time constant are significant in servo applications where reactions to motion commands are highly desirable.

IV. MAGNET SHAPES:

For linear motors, actuators, solenoids and devices of this nature, the magnets needed are shaped from blocks which are essentially rectangular. Magnets have always been made available in block form, with the preferred direction of orientation being through the smallest dimension. So when it came to building rotary motors, especially in the prototyping stage, arcs had to be machined out of these blocks (Figure 3). Machining was a difficult and sometimes dangerous job, especially with SmCo material. Rings of magnets were made up of several arc segments. In production, these segments were pressed with a radial orientation to maximize the amount of flux produced when used in a motor.

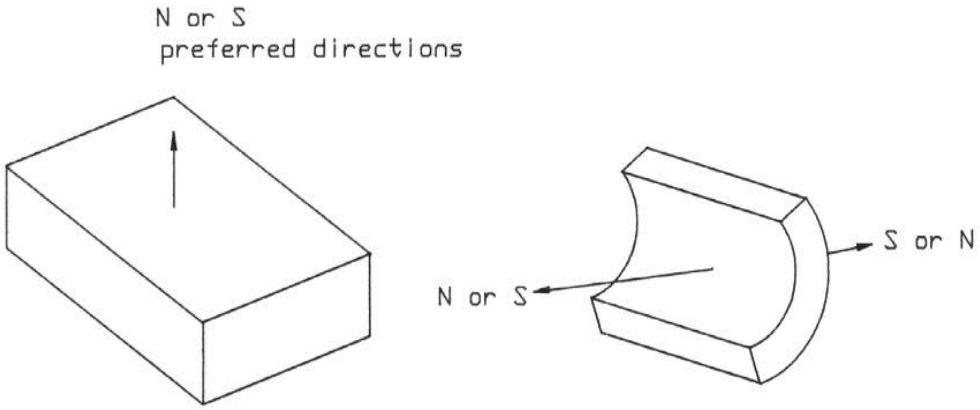
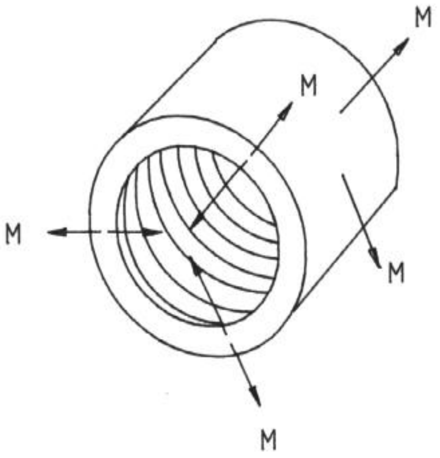


Figure 3 : Anisotropic magnets



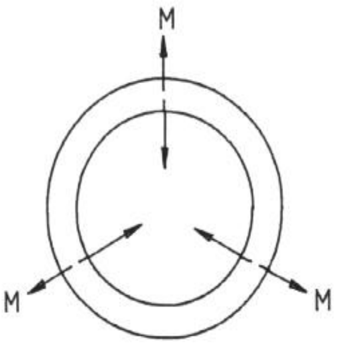


Figure 4 : Radial orientation

It was a while before complete rings were being produced with radial orientation (Figure 4). This is now available using NdFeB materials. The obvious advantage is that each pole on the surface of the ring is very close to 180° electrical, or full-pitch. The transition in polarity between adjacent poles can be made very small and on the order of one or two air-gap lengths. However, rings are not available for large diameter motors and arcs must, therefore, still be used. In such cases, the arc lengths are usually less than 180° electrical by up to 30%. This reduction from the maximum value results in a flux-density distribution in the air-gap more like a sinusoid than a rectangle. The wave shapes of the back emf and torque are similar to that of the flux-density.

It is expensive to produce ground, accurate edges on arc segments and the segment width, therefore, is usually variable. If each arc segment is magnetized as a single pole, the poles will have somewhat varying strengths. It is also difficult to accurately adjust the gaps between segmented magnets, especially if they are assembled after being magnetized. If the magnets are on a rotor, considerable imbalance may result, and must be corrected. Ring magnets, on the other hand, are generally very well balanced and require only fine adjustment. Often the balancing operation can be eliminated altogether. It is possible to pre magnetize the ring magnets before assembly without adding greatly to the manufacturing difficulty. If a ring magnet is magnetized in place, there is no need to orient the part in the fixture, as must be done with segments. Because only one part is handled, assembly time is reduced. Since usually only one part is needed per electromagnetic device, ring magnets often cost less to manufacture and ship.

There is also the advantage of being able to stack magnet rings next to each other to produce motors of various axial lengths. When using a ring magnet in a particular design, it must ultimately be hard-tooled before going into volume production In this process, the correct dimensions is cost). To avoid the cost of making the ring magnet to the significantly reduced (from the machining cost of making several dies of the same magnet to different lengths, the rings are simply stacked in as many numbers as required by the various lengths of motor being produced. This is a large saving in tooling cost, a reduction in the number of magnets in inventory and the continuation of a uniform and simple assembly method.

Several companies make magnetic rings with radial orientation by injection-molding of magnetic particles in a plastic binder. The resulting magnets are dimensionally accurate (typically +/- .001 inch), mechanically strong, shock-resistant and inexpensive. They are not very powerful, however, because of the relatively low volume of magnetic material to the total volume as allowed by the process (typically 40% or less).

Another process used to make ring magnets is more expensive but produces parts which are magnetically more powerful. Magnetic powder, which is usually pre coated with a plastic binder, is measured and poured into a mold cavity. An orienting magnetic field is applied and the parts are then pressed axially (sometimes with added heat) to form the part. Magnets made in this way are dimensionally accurate without grinding and have magnetic strengths intermediate between injection-molded parts and those made of solid, sintered material. They are often more fragile, however, than parts made by other means.

V. PERFORMANCE ISSUES:

Many advances in motor design, leading to improvements in performance, result from new methods of calculation or a new arrangement of the various essential parts. A lot of advances are also made from new materials being made available to the designers. One such case is the NdFeB magnet material. The discussion in Section III on Motor Design highlights these gains and their contribution to the final performance.

The introduction of these high energy materials has enabled the designs to address some performance issues, e.g. cogging torque. Permanent magnet motors are characterized by the presence of cogging torque, resulting from the permanent presence of the magnetic field in the motor. This torque manifests itself by uneven movements of the rotor and the presence of stable positions over one revolution. The amount of torque produced depends on many factors: the size of the motor; the energy of the magnets; the width of the air-gap between magnet and steel; the shape of the magnet; and the number of poles and teeth used.

The torque can be very high when using a high energy magnet material like NdFeB, but can be reduced with appropriate design choices. The choice of pole/tooth ratio is very effective but skewing is even more effective in reducing this torque. Skewing is a gradual misalignment between the edge of a pole (or edge of a tooth) with respect to the axis of the motor (Figure 5).

Skewing results in averaging out the reluctance between stator and rotor as the poles face a fairly constant amount of steel. The skewing of the teeth can make the winding process more difficult since the slot openings are no longer parallel to the axis. If this is a problem, skewing the poles becomes a desirable alternative. To achieve skewed poles, the magnets are magnetized with the appropriate skew using specially designed magnetizing fixtures.

The solution to the cogging torque problem has become easier with the availability of NdFeB magnets. First because they are easier to magnetize than other rare earth materials (Section III.E.) and second, because they are available in ring form. When using a ring, it is magnetized with the total number of poles and with the required skew angle. If however, a ring is not available, individual segments of magnets would need to be shaped with the appropriate skew and magnetized separately. This adds to the cost when compared with a complete ring.

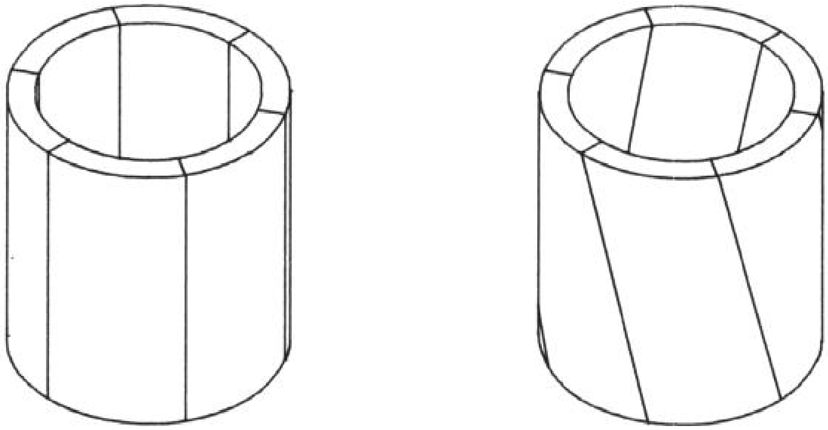


Figure 5: Straight and skewed magnetic poles

The magnetic losses experienced in a motor are always a critical part of the performance characteristics in a new design. They are made up of hysteresis and eddy-current losses and are primarily found in steel. The amount of these losses depends on the flux-density level and the frequency of change of flux direction in the steel. In view of the high operating levels of flux-density when using NdFeB magnets, adjustments to the design are necessary to keep these losses under control. For example, increasing the cross-sectional areas of steel in the flux path and using a high-saturation steel are solutions to these requirements. The magnet itself experiences such losses also, as a result of being in the same changing magnetic field. The value of flux-density and frequency may be different from those in other parts of the motor, but can still produce significant losses. The eddy-current losses are, additionally, a function of the electric resistivity of the material experiencing the loss. Fortunately, NdFeB materials have a comparable value of resistivity to other rare earth magnet materials. Hence no extra loss is added to the total motor losses as a result of the losses in these magnets.

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