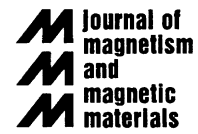




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Topical review

## Permanent magnet applications

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### Abstract

Rare-earth permanent magnets are ideally suited to generate magnetic fields comparable to their spontaneous polarization  $J_S$ . Near-square hysteresis loops and large values of the coercivity and anisotropy fields greatly simplify magnet design, as each magnet block is effectively transparent to the magnetic fields produced elsewhere in the magnet assembly. The fields generated by compact and efficient magnet structures requiring no continuous expenditure of energy can be static or variable, uniform or nonuniform. Permanent magnets are fully competitive with electromagnets for fields up to 2 T, and fields as high as to 5 T can be produced in a small volume. When a field with a rapid spatial variation is required, permanent magnets may offer the only practicable solution. Both permanent magnet structures and the uses to which they are put are reviewed, classifying the magnet applications in terms of the nature of the field, the effect on the magnet and the physical effect exploited. © 2002 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

Permanent magnets are unique in their ability to deliver magnetic flux into the airgap of a magnetic circuit without any continuous expenditure of energy [1]. The flux density may be uniform or nonuniform, steady or time varying. Magnet applications can also be classified by their influence on the magnet or by the physical effect that is being exploited. A summary of magnet applications is provided in Table 1. Although the list is quite extensive, permanent magnets are really just beginning to be appreciated and exploited. On

account of their versatility and economy, permanent magnets are finding numerous new applications, besides replacing electromagnets for many purposes.

We first expand briefly on the different physical effects mentioned in the Table. A steady uniform field may be used to generate torque  $\Gamma$  or align existing magnetic moments  $m$  since  $\Gamma = m \cdot B$ . The corresponding quantum phenomenon is Zeeman splitting of atomic or nuclear energy levels. Particles of charge  $q$  moving through the uniform field with velocity  $v$  are deflected by the Lorentz force  $F = qv \cdot B$ , which causes them to move in a helix in free space with the cyclotron frequency  $f_c = eB/2\pi m_e$ ; 28 GHz/T for an electron. When the electrons are confined to a conductor of length

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Table 1  
Summary of permanent magnet applications

Field	Magnetic effect	Type	Examples
Uniform	Zeeman splitting	Static	Magnetic resonance imaging
	Torque	Static	Alignment of magnetic powder
	Hall effect, magnetoresistance	Static	Sensors, read-heads
	Force on conductor	Dynamic	Motors, actuators, loudspeakers
	Induced emf	Dynamic	Generators, microphones
Nonuniform	Force on charged particles	Static	Beam control, radiation sources (microwave, uv, X-ray)
	Force on magnet	Dynamic	Bearings, couplings, Maglev
	Force on paramagnet	Dynamic	Mineral separation
Time varying	Varying field	Dynamic	Magnetometers
	Force on iron	Dynamic	Switchable clamps, holding magnets
	Eddy currents	Dynamic	Metal separation, brakes

$L$  aligned perpendicular to the field, as in the armature of a motor or actuator, they constitute a current  $I$ , and the Lorentz force leads to the familiar expression  $F = BIL$ . Conversely, moving a conductor through the field produces an induced emf given by Faraday's law  $\varepsilon = -d\Phi/dt$  where  $\Phi$  is the flux threading the circuit of which the conductor forms a part.

Spatially nonuniform fields offer another series of potentially useful effects. They exert a force on a magnetic moment given by the energy gradient,  $F = \nabla(m \cdot B)$ . They also exert nonuniform forces on charged particles, which can be used to focus ion or electron beams or to generate intense electromagnetic radiation in a synchrotron wiggler. The ability of rare-earth permanent magnets to generate complex flux patterns with rapid spatial variation ( $\nabla B > 100 \text{ T/m}$ ) is unsurpassed by any electromagnetic device. The Amperian surface current equivalent to a magnet with  $J_S \approx 1 \text{ T}$  is  $800 \text{ kA m}^{-1}$ . Solenoids, whether resistive or superconducting, have to be several centimeters in diameter to accommodate the requisite Ampere-turns, whereas blocks of rare-earth or ferrite magnets of any size can be assembled in any desired orientation as close to each other as necessary.

Variable or time-varying fields can be produced by displacing or rotating the magnets, or by moving soft iron in the magnetic circuit. They may induce an emf according to Faraday's law

and exert forces on the resulting Eddy currents in a conductor. Alternatively, they may be used to switch on or measure continuously the other effects of a field, for example, in a magnetization measurement.

Viewed from the standpoint of the permanent magnet, the applications are classified as *static* or *dynamic* according to whether the working point of the magnet in the second quadrant of the hysteresis loop is fixed or moving. Its position depends on the magnitude of the  $H$ -field to which the magnet is subjected, which depends in turn on the magnet shape, the airgap and the fields generated by any electric currents flowing in the vicinity. On account of their square loops, oriented ferrite and rare-earth magnets are well-suited for dynamic applications that involve changing flux density in the magnet. Ferrites and bonded metallic magnets also minimize Eddy current losses. The working point changes whenever permanent magnets move relative to each other, when the airgap changes or if there are time-varying currents. In the former cases, there is mechanical recoil when the working point moves along the loop as the airgap changes from a narrow one to a wider one during operation. In the latter case, the recoil is active because the magnets in motors and similar devices are subject to an  $H$ -field during operation as a result of currents in the copper windings. The field is greatest at startup, or in the stalled condition. Provided  $\mu_0 H_c$  exceeds  $B_r$ ,

it is possible to drive the working point momentarily into the third quadrant of the  $B:H$  loop without demagnetizing the permanent magnet. The intrinsic coercivity  $iH_c$  may be as important a figure of merit as the energy product  $(BH)_{max}$  in this type of application.

The properties of some typical magnet grades are summarized in Table 2. Magnets nowadays are usually squat cylinders with a demagnetizing factor  $N \approx \frac{1}{2}$ , because the working point then corresponds to maximum energy product [1]. As the energy product of permanent magnets has increased, there has been a trend towards miniaturization and moving-magnet designs. Permanent magnet devices have become smaller and lighter. The number of parts is reduced, for example, by shifting the magnets of a brushless DC motor to the rotor and moulding the magnets together with the shaft and gear in one piece. Moving magnets have low inertia, and the stationary windings can be thermally heat-sunk. The benefit of permanent magnets in small magnetic circuits can be appreciated by comparing a small disk-shaped magnet with a coil having the same magnetic moment. A disk of diameter 8 mm and height 2 mm made of a material with magnetization  $M = 1 \text{ MA/m}$  has magnetic moment  $m \approx 0.1 \text{ Am}^2$ . An equivalent coil of the same diameter would require an impossible 2000 A turns.

An overall breakdown of permanent magnet applications is given in Fig. 1. Hard ferrites account for 55% of the market by value, rare-earth magnets are at 35%, and most of the remainder is alnico. In volume terms, global production averages to about 80 g of hard ferrite

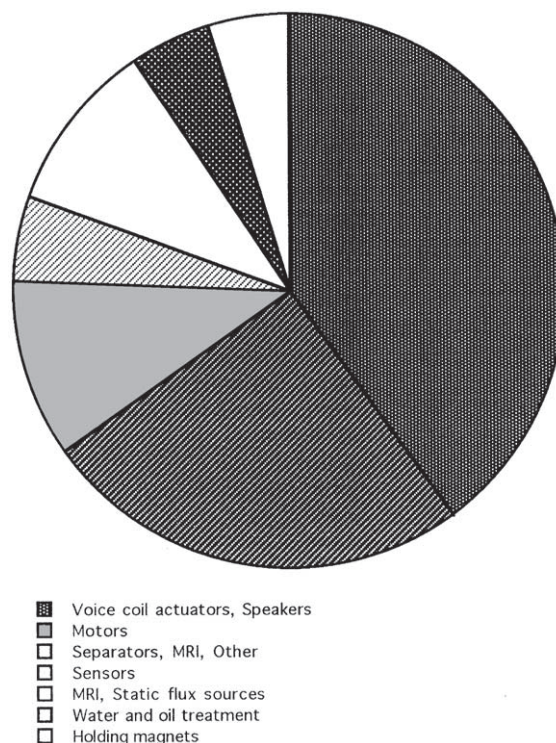


Fig. 1. Summary of permanent magnet applications.

Table 3  
Temperature coefficients and maximum operating temperatures for permanent magnets

	$T_c$ (°C)	$dM_s/dT$ (%)	$dH_c/dT$ (%)	$T_{max}$ (°C)
$\text{SrFe}_{12}\text{O}_{19}$	450	-0.20	0.40	300
Alnico	800	-0.02	0.03	500
$\text{SmCo}_5$	720	-0.04	-0.20	250
$\text{Sm}_2\text{Co}_{17}^*$	820	-0.03	-0.20	350
$\text{Nd}_2\text{Fe}_{14}\text{B}$	310	-0.13	-0.60	120

\*Intergrown with 1:5 phase.

Table 2  
Characteristics of typical commercial-oriented magnets

	$B_r$ (T)	$J_s$ (T)	$iH_c$ ( $\text{kA m}^{-1}$ )	$BH_c$ ( $\text{kA m}^{-1}$ )	$(BH)_{max}$ ( $\text{kJ m}^{-3}$ )
$\text{SrFe}_{12}\text{O}_{19}$	0.41	0.47	275	265	34
Alnico	1.25	1.40	54	52	43
$\text{SmCo}_5$	0.88	0.95	1700	660	150
$\text{Sm}_2\text{Co}_{17}^*$	1.08	1.15	800	800	220
$\text{Nd}_2\text{Fe}_{14}\text{B}$	1.28	1.54	1000	900	300

\*Intergrown with 1:5 phase.

and 1 g of rare-earth magnet for everyone on Earth.

Motors and actuators account for most of the magnets produced. Electrical machines can run at temperatures in excess of 100°C, and there is an ongoing effort to develop new materials that can be used up to 400°C [3]. Magnetization and coercivity naturally decline as the Curie point is approached; the temperature coefficients of these quantities around ambient temperature are listed in Table 3. The maximum temperatures at which

typical magnets can safely be used are also indicated in the table.

## 2. Applications

An account of the main applications is now given, with emphasis on permanent magnet structures as flux sources [4–6]. When blocks of rare-earth or ferrite magnets are placed in contact, the field of one magnet does not significantly perturb the magnetization of its neighbours, because the longitudinal susceptibility is zero for a square hysteresis loop and the transverse susceptibility  $M_s/H_a$  is only of order 0.1, since the anisotropy field  $H_a$  is much greater than the magnetization (Table 4). The directions of magnetization of two blocks of  $\text{SmCo}_5$  in contact with their easy directions perpendicular, for example, will deviate by less than a degree from the easy

directions. A consequence of the rigidity of the magnetization is that the superposition of flux produced by rare-earth permanent magnets is linear, and the magnetic material is effectively transparent, behaving like vacuum with permeability  $\mu_0$ . Transparency and rigidity greatly simplify the design of magnetic circuits [2]. The flux density in the airgap  $B_g(\mathbf{r})$  scales with, but is not limited by the remnant polarization of the magnet material;

$$B_g(\mathbf{r}) = K(\mathbf{r})B_r(\mathbf{r}).$$

Here,  $K(\mathbf{r})$  is the geometric constant of the magnetic circuit; when  $K > 1$ , the circuit achieves flux concentration [4].

### 2.1. Flux sources

(a) *Uniform fields*: The magnetic field produced by a point dipole of moment  $m$  ( $\text{Am}^2$ ) is quite

Table 4  
Intrinsic magnetic properties of phases used in permanent magnet manufacture

Compound		$T_C$ ( $^\circ\text{C}$ )	$M_s$ ( $\text{MA m}^{-1}$ )	$J_s$ (T)	$K_1$ ( $\text{MJ m}^{-3}$ )	$H_a$ ( $\text{MAm}^{-1}$ )	$J_s^2/4\mu_0$ ( $\text{kJ m}^{-3}$ )
$\text{BaFe}_{12}\text{O}_{19}$	Hexagonal	450	0.38	0.47	0.25	1.1	44
$\text{SmCo}_5$	Hexagonal	720	0.84	1.05	17	32	219
$\text{Sm}_2\text{Co}_{17}$	Rhombohedral	827	1.04	1.30	3.3	5.1	336
$\text{Nd}_2\text{Fe}_{14}\text{B}$	Tetragonal	312	1.29	1.61	4.9	6.1	516
$\text{Sm}_2\text{Fe}_{17}\text{N}_3$	Rhombohedral	476	1.23	1.54	8.6	11.2	472

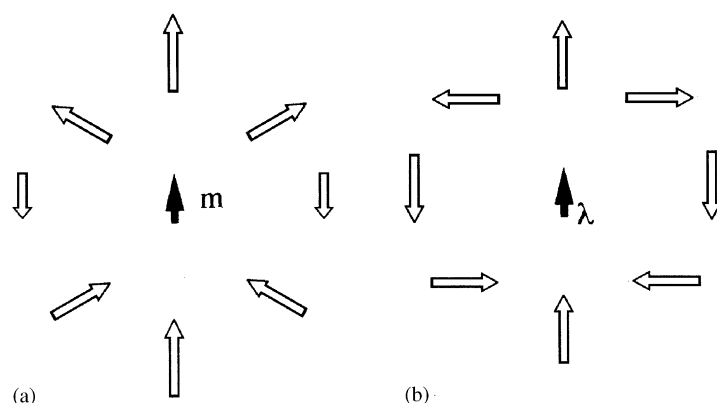


Fig. 2. Comparison of the magnetic field pattern produced: (a) by a point dipole of moment  $m$ , and (b) a line dipole with moment  $\lambda$  per unit length.

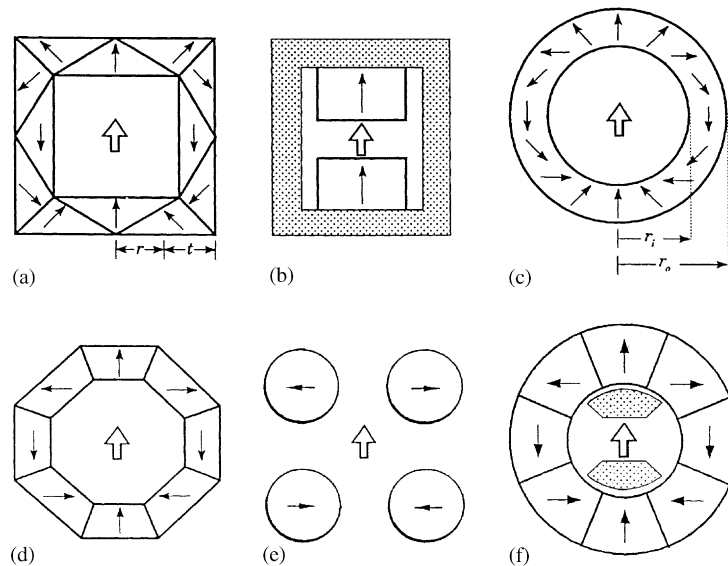


Fig. 3. Cross-section of some permanent magnet structures which generate a uniform magnetic field in the direction shown by the hollow arrow. Magnets are unshaded; the shaded material is soft-iron.

nonuniform (Fig. 2a). In polar coordinates

$$\begin{aligned} H_r &= 2m \cos \theta / 4\pi r^3, & H_\theta &= m \sin \theta / 4\pi r^3, \\ H_\phi &= 0 \end{aligned} \tag{1}$$

so the magnitude and direction of  $H$  depend both on  $r$  and  $\theta$ . The field due to an extended line dipole of moment  $\lambda$  (Am) is different

$$\begin{aligned} H_r &= \lambda \cos \theta / 2\pi r^3, & H_\theta &= \lambda \sin \theta / 2\pi r^3, \\ H_\phi &= 0 \end{aligned} \tag{2}$$

so the magnitude of  $H$ ,  $\sqrt{(H_r^2 + H_\theta^2 + H_\phi^2)}$ , is actually independent of  $\theta$ ; its direction makes an angle  $\eta = 2\theta$  with the orientation of the magnet (Fig. 2b).

By assembling long cylindrical magnet segments around a hollow bore it is possible to create a field which is uniform within a certain region of space and zero elsewhere [4–6]. Choosing the orientation of each segment appropriately, the fields will all add at the centre. In the transverse field design shown in Fig. 3a, the outer surface will be an equipotential provided  $t/r = \sqrt{2} - 1$ , in which case the flux density in the airgap is  $0.293B_r$  [2]. Multiples of this field can be obtained by nesting similar structures inside each other. Shimming to

compensate any imperfections in the magnets or assembly is possible by placing appropriate compensating dipoles in the corners. Open cylinders or permanent magnets with iron yokes (Fig. 3b) provides highly uniform fields (better than one part in  $10^5$ ) which may be used for magnetic resonance imaging. Permanent magnet flux sources supply fields of order 0.3 T in whole-body scanners. Fields are lower than those of competing superconducting solenoids, but there is no need for any cryogenic installation. Nuclear magnetic resonance spectrometers with permanent magnets flux sources are finding applications for quality control in the food, polymer and construction industries.

Fig. 3c shows a different design where the direction of magnetization of any segment is at an angle  $\eta = 2\theta'$  from the vertical axis. According to Eq. (2), all segments now contribute to create a uniform field across the airgap in the vertical direction. Unlike the structure of Fig. 3a, the radii  $r_1$  and  $r_2$  can take any values without creating a stray field outside the cylinder. The device is commonly known as a Halbach cylinder, although it was suggested earlier by Mallinson [7]. The flux density in the airgap of a

long cylinder is

$$B = B_r \ln(r_2/r_1), \quad (3)$$

where  $r_1$  and  $r_2$  are the inner and outer radii. In practice, it is convenient to assemble the device from  $n$  trapezoidal segments, as illustrated in Fig. 3d for  $n = 8$ . In that case, an extra factor  $[\sin(2\pi/n)]/(2\pi/n)$  must be included on the right-hand side of Eq. (3). Furthermore, the cylinders are never infinitely long; the length is typically comparable to the diameter, so the geometric constant  $K$  is reduced by an amount  $\Delta K = (z/2)[1/z_0 - 1/z_i] + \ln[(z + z_0)/(z + z_i)]$  where  $z$  is the distance from the centre,  $z_0 = (z_2 + r_0^2)^{1/2}$  and  $z_i = (z_2 + r_i^2)^{1/2}$  [8]. For example, the flux density at the centre of an octagonal cylinder with  $r_1 = 12$  mm,  $r_2 = 40$  mm and length 80 mm made of a grade of Nd–Fe–B having  $B_r = 1.20$  T is  $B_g = 1.25$  T, compared to the value of 1.44 T calculated from Eq. (3). Here is an example of an ironless magnetic circuit with  $K > 1$ , illustrating the idea of magnetic flux concentration. It is also possible to introduce iron into the airgap to enhance the field at the centre (Fig. 3e).

Large cylindrical magnets of the Halbach-type weighing several tonnes are used for magnetic annealing of wafers up to 200 mm in diameter in a field of  $\approx 1$  T for the manufacture of spin valve read heads and magnetic random-access memories.

Assemblies composed of pairs of magnetized wedges allow great flexibility in the shape of the cavity while offering efficiencies comparable to those of Halbach cylinders [9]. A different simplification of the basic structure employs transversely magnetized cylindrical rods, as shown in Fig. 3e [10]. This allows both longitudinal and transverse access to the cavity. The geometrical constant at the centre for a set of  $n$  rods which are just touching is

$$K = (n/2)\sin^2(\pi/n). \quad (4)$$

By increasing  $n$ , the central region in which the field is uniform is enlarged, but the magnitude of the field itself is reduced.

The limit to the fields that can be generated using permanent magnets is about 5 T, which has recently been achieved in a tiny cavity in a

spherical magnet structure [11]. The limit is set in part by the coercivity of the material. The vertical segments in Fig. 3 are subject to a reverse  $H$ -field equal to the field in the bore. But there is also a practical size limitation imposed by the exponential increase in dimension of Eq. (3). Admitting a material existed with  $B_r = 1.5$  T and  $\mu_0 H_c = 5$  T, the diameter required to achieve 5 T in a 25 mm bore is 700 mm. Such a structure 400 mm high would weight about a tonne.

(b) *Nonuniform fields*: The cylindrical configurations of Fig. 3 may be modified to produce a variety of nonuniform fields such as quadrupole fields, particularly useful for charged-particle beam control [12]. Higher multipole fields than dipole are obtained by having the orientation of the magnets in the ring vary as  $\eta = (1 + (n/2))\theta$ , where  $n = 2$  for a dipole field,  $n = 4$  for a quadrupole and so on. The field at the centre of the quadrupole is zero, but whenever the particle beam deviates it experiences an increasing field which causes its trajectory to curve back to the centre. Coaxial dipole rings known as “magnetrons” are used in sputtering systems to increase the ionization of the plasma near the target by extending the paths of the electrons into helices around the field lines. The magnets in an ion pump have a similar function. The magnetrons in domestic microwave ovens are devices where electrons emit cyclotron radiation as they move in trajectories determined by the field of a ferrite ring magnet.

A variant of the normal multipole Halbach configuration is the external Halbach configuration where the orientation  $\eta$  varies as  $(1 - (n/2))\theta$ . The multipole field is then produced outside the cylinder. The case of  $n = 2$  (uniform magnetization) produces a dipole field outside the cylinder, and zero field in the bore. The case  $n = 4$ , illustrated in Fig. 4c, produces a quadrupole field outside the cylinder and zero field inside. The external Halbach designs are useful for the rotors of permanent magnet electric motors.

Other arrangements of cylindrical magnets produce a uniform magnetic field gradient along a particular direction (Fig. 4d). Field gradients are especially useful for exerting forces on other magnets.

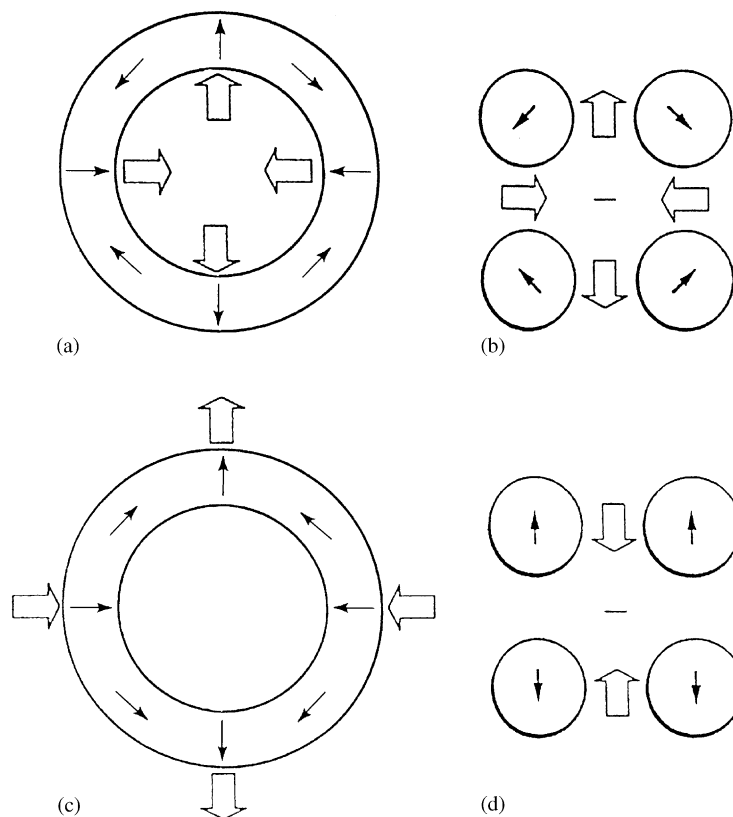


Fig. 4. Cross-section of some permanent magnet structures which generate non-uniform magnetic fields (a), (b) quadrupole fields, (c) an external quadrupole field, and (d) a field gradient.

Another type of permanent magnet structure creates a nonuniform magnetic field along the axis of the magnet, which is the direction of motion of a charged particle beam [2]. Microwave power tubes such as the travelling wave tube are designed to keep the electrons moving in a narrow beam over the length of the tube and focussing them at the end while coupling energy from an external coil. The design with  $\text{SmCo}_5$  magnets generating a periodic axial field in Fig. 5a is compact, and uses no power. One period of the structure in Fig. 5a generates an axial field gradient, known as a cusp field. Uses of cusp fields include the stabilization of molten metal flows. Fields of alternating direction are also used in magnetic water treatment.

Insertion devices for generating intense beams of hard radiation (uv and X-ray) from energetic

electron beams in synchrotron sources create a periodic transverse field. These devices are known as wigglers, since they cause the electrons to travel in a sinuous path. Similar structures are used in free-electron lasers. A design including segments magnetized in the parallel direction to concentrate the flux is shown in Fig. 5b.

(c) *Variable fields:* Fields can be varied by changing the airgap, or by some movement of the magnets or iron in a structure with respect to each other. The working point is displaced as the magnets move so these devices involve mechanical recoil. A simple type of variable flux source is a switchable magnet (Fig. 6). These are often used in holding devices, where a strong force is exerted on a piece of ferrous metal in contact with the magnet. The working point shifts from the open circuit point to the remanence point where  $H = 0$

as the circuit is closed. The maximum force  $F$  that can be exerted at the face of a magnet of area  $A_m$  where the flux density is  $B_r$  is given by

$$F/A_m = B_r^2/2\mu_0. \quad (5)$$

Forces of up to  $40 \text{ N cm}^{-2}$  can be achieved for  $B_r = 1 \text{ T}$ .

Simple force applications in catches and closures consume large amounts of sintered ferrite. Bonded

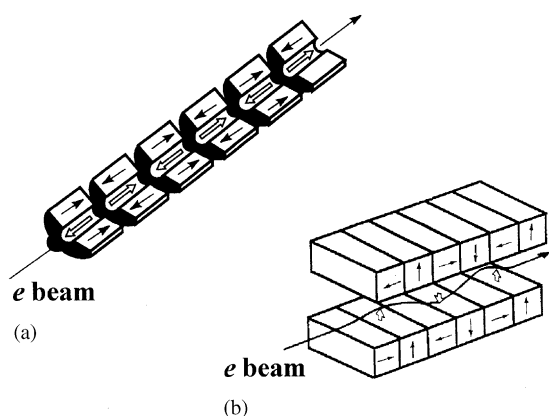


Fig. 5. Periodic flux sources: (a) a magnet for a microwave travelling-wave tube and (b) a wiggler magnet used to generate intense electromagnetic radiation from an electron beam.

ferrite magnetized in strips of alternating polarity is widely used for fixing signs and light objects to steel panels such as refrigerator doors.

To create a uniform variable field, two Halbach cylinders of the type shown in Fig. 3 with the same radius can be nested inside each other as shown in Fig. 7a. Then by rotating them through an angle  $\pm\alpha$  about their common axis, a variable field  $2\cos\alpha B_r \ln(r_2/r_1)$  is generated. No torque would be needed to rotate two ideal Halbach cylinders, but in practice some torque arises from the segmented structure and end effects [13].

Another solution (Fig. 7b) is to rotate the rods in the device of Fig. 3f [14]. By gearing a mangle with an even number of rods so that the alternate rods rotate clockwise and anticlockwise through an angle  $\alpha$ , the field varies as  $B_{\max} \cos\alpha$ . Further simplification is possible with a magnetic mirror, a horizontal sheet of soft iron containing the axis of symmetry which produces an inverted image of the magnets, and halves the number required [2]. The torque needed to vary the field in a mangle increases with decreasing number of rods. A variable field gradient can also be obtained in the mangle [14]. A movable axial field gradient can be obtained with nonuniformly magnetized rods [15].

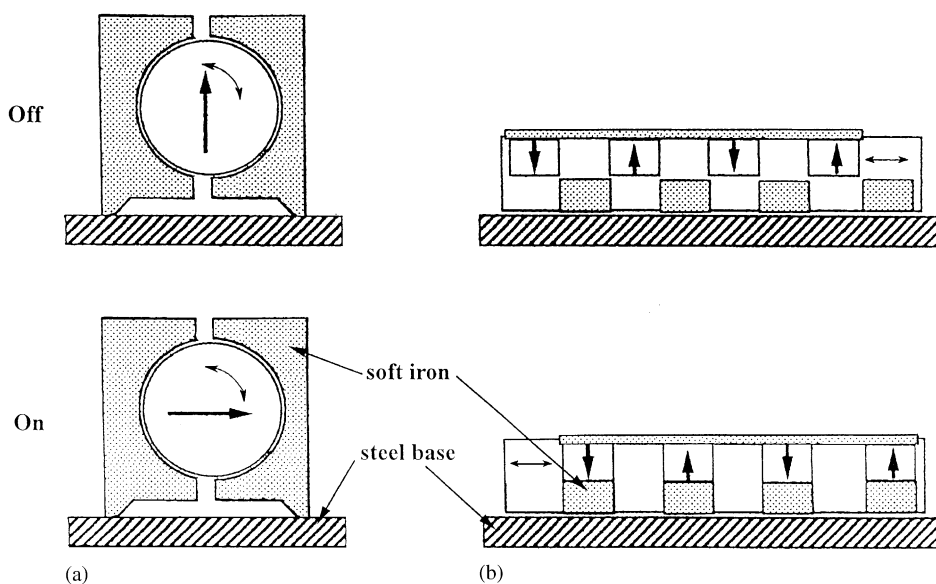


Fig. 6. Two design for switchable permanent magnets.



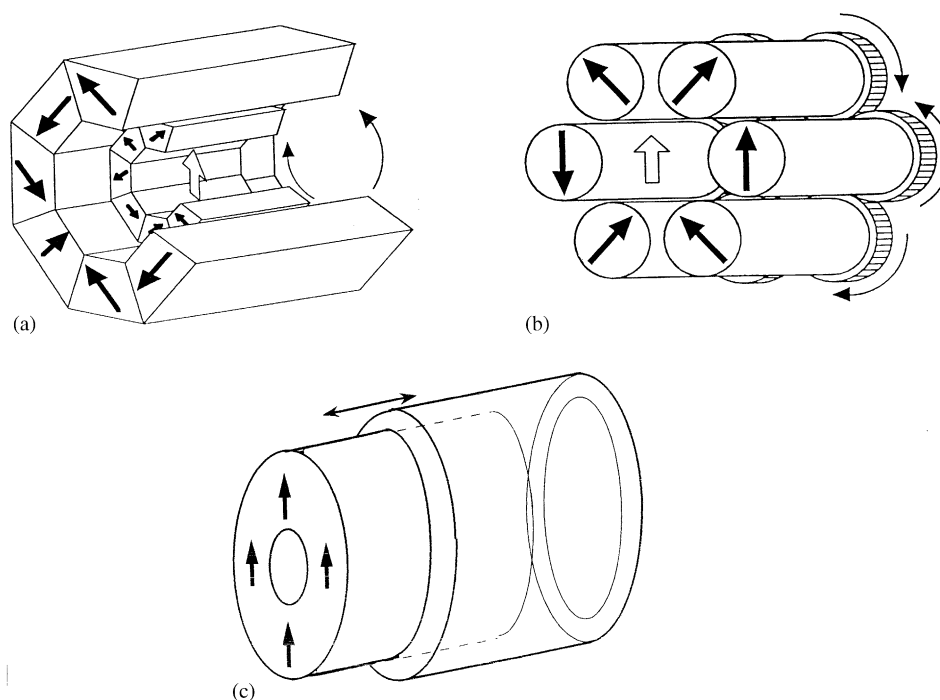


Fig. 7. Permanent magnet variable flux sources: (a) a double Halbach cylinder, (b) a four-rod magnetic mangle, and (c) an external dipole ring with a movable iron sheath.

These permanent magnet variable flux sources are compact and particularly convenient to use since they can be driven by stepping or servomotors and they have none of the high power and cooling requirements of a comparable electromagnet. A typical commercial flux source of the design shown in Fig. 7a uses 20 kg of Nd–Fe–B magnets to generate a field up to 2.0 T in a 25 mm bore. Rotating or alternating fields can be generated by rotating the magnets continuously.

A variable flux source can also be made from a uniformly magnetized magnet ring with a hole (the  $n = 2$  external Halbach cylinder) and a movable iron sheath (Fig. 7c). When the sheath fully covers the cylinder, flux is confined within the bore, where previously it was zero [16].

Permanent magnet variable flux sources are expected to displace resistive electromagnets to generate fields of up to about 2.0 T, but they cannot compete with superconducting solenoids in the higher field range.

## 2.2. Couplings and bearings

Permanent magnets are useful for coupling rotary or linear motion when no contact between members is allowed [17]. Fig. 8 illustrates the design of two magnetic bearings, a simple rotary coupling, and a magnetic gear. Forces depend quadratically on the remanence of the magnets, so it is advantageous to select material with a large polarization. If the coupling slips, the magnets may be subjected to a substantial reverse field, so high coercivity is also needed. Rare-earth magnets are ideal. The maximum torque can be varied by adjusting the airgap, and values of order 10 Nm may be achieved in couplings a few centimeters in dimension.

Magnetic bearings are simple, cheap and reliable. They are best suited to high-speed rotary suspensions, in flywheels or turbopumps for example. Linear suspensions have been tested in prototype magnetically levitated transportation systems. The simplest bearings are made of two

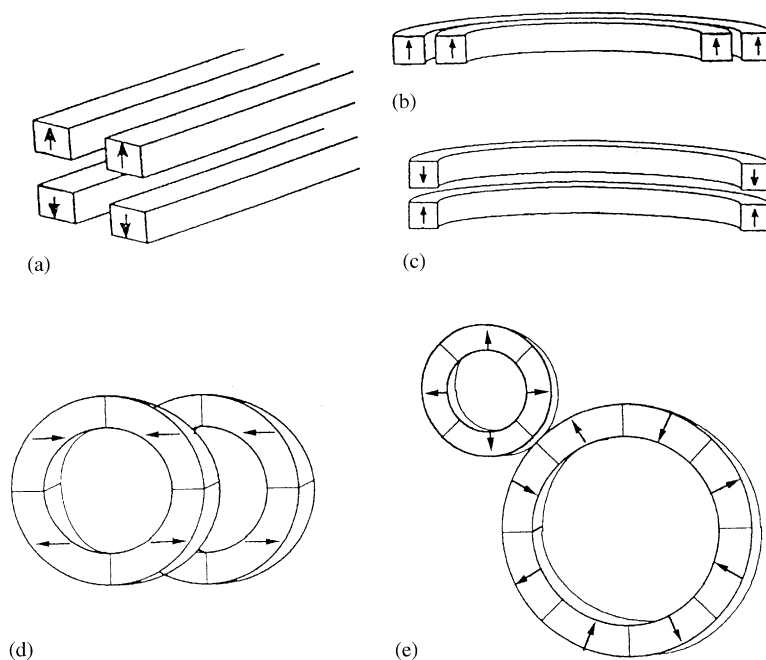


Fig. 8. Some magnetic bearings and couplings: (a) is a linear bearing, (b) and (c) are rotary bearings, (d) is a face-type coupling and (e) is a magnetic gear.

ring-shaped magnets in repulsion (Fig. 8b and c). Some configurations provide radial restoring force provided the axis is prevented from shifting or twisting. Others support a load in the axial direction, but must be prevented from moving in the radial direction. The linear magnetic bearings provide levitation along a track, but lateral constraint is required. It is impracticable to equip a great length of track with permanent magnets, so instead levitation may be provided by repulsion from Eddy currents generated in a track of aluminium plates, or by attraction of the magnets on the vehicle to a suspended iron rail.

It is a feature of bearings made entirely of permanent magnets that a mechanical constraint (or active electromagnetic support) is generally required in one direction. Unfortunately, it is impossible to design a static field configuration which will draw a small magnet towards a fixed point in space. The field near such a point would have to satisfy the condition that  $dB/dx$ ,  $dB/dy$  and  $dB/dz$  are all negative, which contradicts Maxwell's equation  $\nabla \cdot \mathbf{B} = 0$ . The impossibility of

stable magnetostatic levitation of a magnet at a point is known as Earnshaw's theorem.

Stable levitation is possible, however, when there is another component, specifically a diamagnet or superconductor, which creates an upright image of the permanent magnet. As the magnet moves away from a position of unstable equilibrium, there is a repulsive restoring force as it approaches its image (Fig. 9). The maximum repulsive force for perfect flux expulsion from a superconductor (susceptibility  $\chi = -1$ ) is given by Eq. (5). Normal diamagnets, with  $\chi \approx -10^{-4}$  to  $-10^{-5}$ , produce much weaker images, but they can be used in conjunction with permanent magnets to stabilize a metastable point of levitation for a small magnet.

Greater repulsive forces could be achieved using superconducting 'permanent magnets'. These are usually blocks of melt-textured high-temperature superconductor, in which the trapped flux density  $B_r$  can be as high as 14.4 T [18]. Huge forces, of order  $10^8 \text{ Nm}^{-2}$  (tonnes per square centimeter), are envisageable, but major drawbacks are the

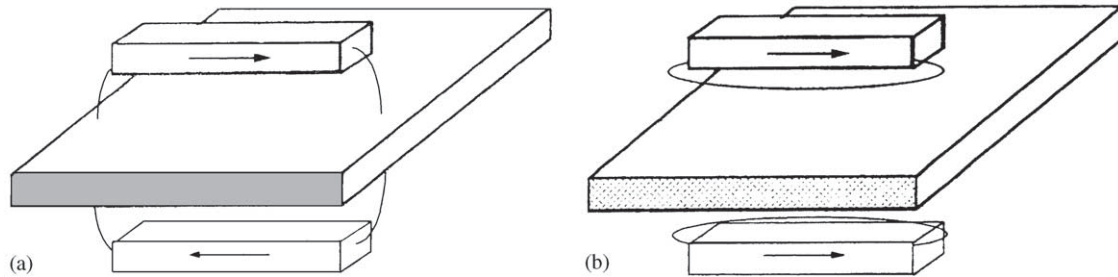


Fig. 9. Images of a permanent magnet in: (a) a soft ferromagnet and (b) a superconductor or strong diamagnet.

difficulty in establishing the flux in the superconductor, and the need for cooling.

### 2.3. Magnetic separation

Magnetic separation is a technology based on nonuniform or time-varying magnetic fields which affords great economic and social benefits. When the moment  $m$  is induced by a field in material of volume  $V$  and susceptibility  $\chi$ , the force is

$$F = (1/2)\mu_0\chi V\nabla(H^2). \quad (6)$$

To separate ferrous and nonferrous scrap or to select minerals from crushed ore on the basis of their magnetic susceptibility it is sufficient to use open gradient magnetic separation where material tumbles through a region where there is a strong magnetic field gradient. A gradient of  $100 \text{ Tm}^{-1}$  produces separation forces of order  $10^8 \text{ Nm}^{-3}$ .

High-gradient magnetic separation is suitable for capturing weakly paramagnetic material such as red blood cells. Here, a liquid containing the paramagnetic solids in suspension passes through a tube filled with a fine ferromagnetic mesh or steel wool which distorts the flux pattern in an applied field, creating local field gradients as high as  $10^5 \text{ Tm}^{-1}$  where separation forces can reach  $10^{11} \text{ Nm}^{-3}$ . The paramagnetic material remains stuck to the wires until the external field is switched off, when it may be flushed out of the system. Switchable permanent magnets can be used to create the field.

A different principle is employed in electromagnetic separation to sort nonferrous metal such as aluminium cans from nonmetallic material in a stream of refuse (Fig. 10). A fast-moving conveyor

belt carries the rubbish over a static or rotating drum with embedded ferrite or rare-earth magnets. The relative velocity of the magnets and the refuse may be  $50 \text{ ms}^{-1}$ . Eddy currents induced in the metal create a repulsive field, and the metal is thrown off the end of the belt in a different direction to the nonmetallic waste. In electromagnetic separation, deflection depends on the ratio of conductivity to density, so it is possible to separate metals such as aluminium, brass and copper.

### 2.4. Sensors

Magnetic sensors are based on detecting a varying field in an airgap using a Hall effect or magnetoresistance probe which delivers a voltage proportional to  $B$ . Magnetic position and speed sensors are used in automobile system controls, where they offer reliable noncontact sensing in a hostile environment involving dirt, vibration and high temperatures. Angular position sensors built into electronically commutated motors can be simple Hall or magnetoresistance sensors which detect the stray field produced by a multipole rotor.

### 2.5. Motors and actuators

Motors and actuators whose operation depends on permanent magnets are produced in huge quantities,  $>10^8$  per year. A household which owned two or three motors 50 years ago may now possess a hundred, in domestic appliances, audio, video and computer equipment, clocks, watches, toys and the car. Most of these are small DC permanent magnet motors. The high-energy

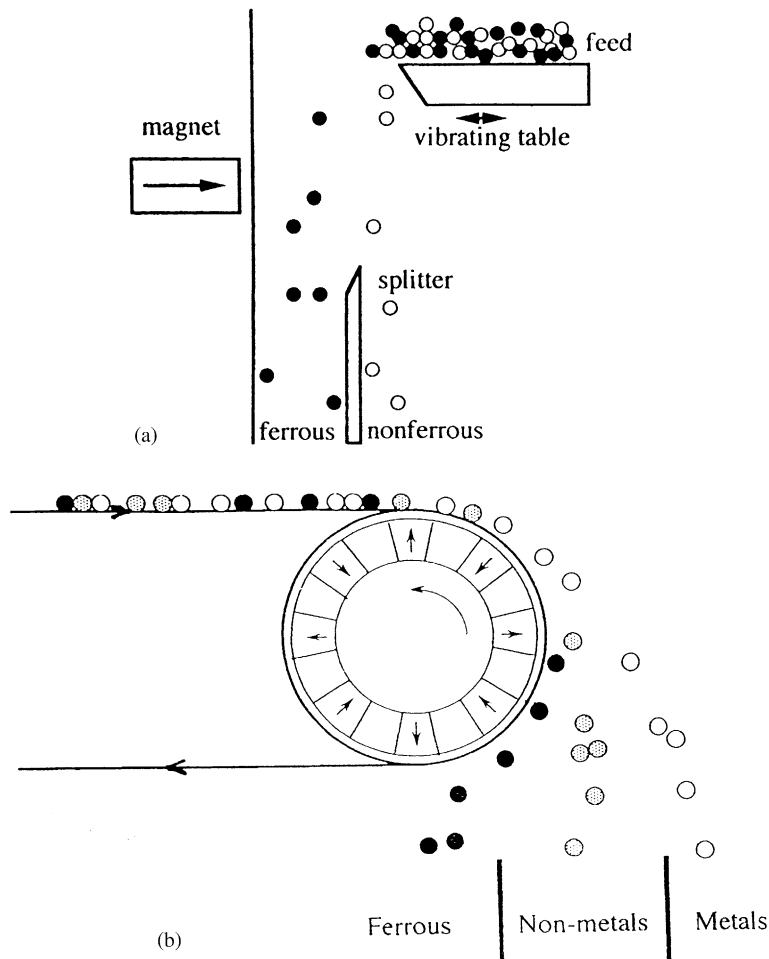


Fig. 10. Electromagnetic separation with permanent magnets.

product high anisotropy of the rare-earth permanent magnets makes it possible to realize compact, low-inertia, high-torque devices—stepper motors, actuators, brushless DC motors—which are the means for electronically regulated motion control. Ferrites are produced in huge quantities for low-cost motors for consumer products, including automobiles. DC servomotors are found in machine tools, robots and other industrial machinery. Permanent magnets can also be used to advantage in large industrial drives, bringing savings in weight, energy and material costs. The ability to fabricate ferrite or rare-earth magnets in any desired shape has led to many

permutations on a few basic electrical machine designs.

An actuator is an electromechanical device with a limited linear or angular displacement [19]. The definition encompasses loudspeakers, microphones, moving-coil meters, print-head actuators, disk-drive head actuators, actuators for industrial robots, pneumatic pumps, car door locks, noise and vibration control using antiphase displacement and many others. Usually, the airgap is fixed, and the working is dynamic due to the  $H$ -field produced by current windings. Actuators tend to be rather simple mechanical structures delivering a force directly to move a load. Three basic

configurations are moving-coil, moving-magnet and moving-iron.

Moving-coil loudspeakers have been built with permanent magnets for over 50 years. Flux is directed into a radial airgap where the voice coil is suspended, attached to a light, rigid cone. The force on the coil is proportional to the flux density in the airgap  $B_g$ , and the acoustic power varies as  $B_g^2$ , which is maximized by operating near the  $(BH)_{\max}$  point of the magnet. Good results are obtained when  $B_g$  exceeds about 0.5 T, and the mass of the voice coil is less than a gram. Designs with cheap flat ferrite ring magnets are inefficient as there is much flux leakage. Efficient moving-magnet designs are feasible using Nd–Fe–B, where a cylindrical magnet is glued to the cone and a stationary drive-coil surrounds it.

A large class of voice-coil actuators are similar in principle to a loudspeaker. Rapid dynamic response is assured by the low mass of the voice coil assembly and the low inductance of the coil in the airgap. A common planar configuration used for head positioning in computer hard-disk drives is shown in Fig. 11. Here a flat coil is attached to a lever which allows it to swing in a limited arc between two pairs of rare-earth magnets. The design requires Nd–Fe–B with the highest possible

energy product ( $>400 \text{ kJ m}^{-3}$ ). Access time at constant acceleration  $a$  is proportional to  $1/\sqrt{a}$ , hence to  $1/\sqrt{B_g}$ . High-grade Nd–Fe–B is also used in the actuators in laser compact-disc players. It is remarkable that various types of voice-coil actuators account for about 40% of Nd–Fe–B production (Fig. 1).

Moving-magnet actuators may be of the linear or rotating variety. They offer low inertia and no flying leads. Linear reciprocating actuators with a stroke of several millimeters are used in pumps operating at frequencies of order 50 Hz, designed to correspond to the resonant frequency of the mechanical system. Rotary actuators can be regarded as electric motors with restricted travel. Moving iron actuators likewise may be linear or rotary. Reed switches, where two flat soft iron reeds are drawn into contact by a magnetic field, can be activated with a solenoid, or simply by moving a magnet.

A vast range of motors can be designed with magnets, their power ranging from microwatts for wristwatch motors, to hundreds of kilowatts for industrial drives [20]. A common DC motor design is shown in Fig. 12a. The permanent magnet on the fixed outer section, known as the stator, creates a field at the windings of the rotor. A mechanical

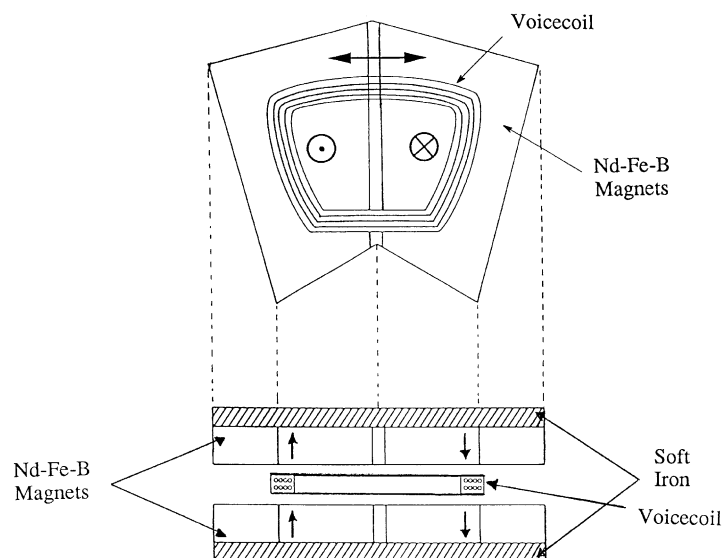


Fig. 11. A flat voice-coil actuator for a personal-computer disk drive.

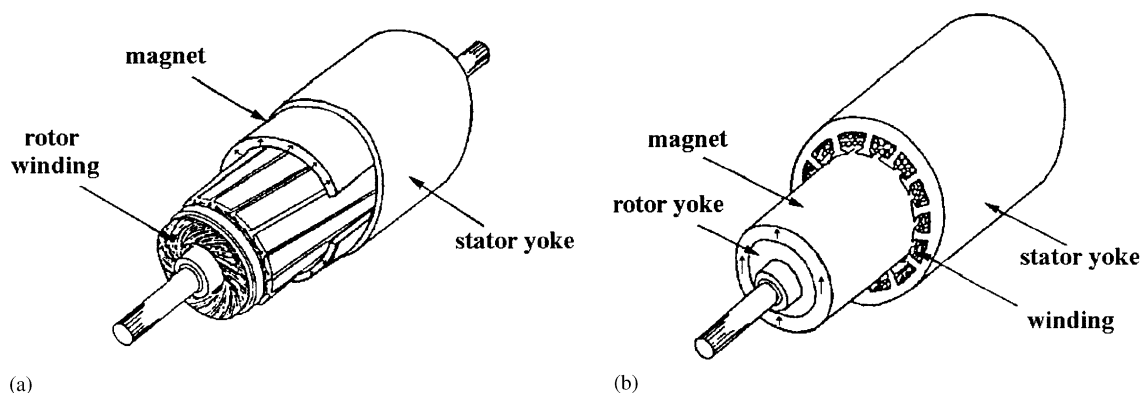


Fig. 12. DC motor designs: (a) brush motor with magnets on the stator and (b) brushless motor with magnets on the rotor.

commutator with brushes distributes current to the windings in such a way that the torque on the rotor is always in the same sense. Conversely, the device will also function as a generator, producing an emf  $U$  if it is driven at an angular velocity  $\omega$ . In a DC servomotor, the torque or the angular velocity is controlled by modifying the applied voltage. Simple velocity control is based on monitoring the back-emf  $U$ , but more sophisticated control systems use a tachogenerator (a small DC motor coupled to the drive shaft) or a precise position encoder to generate the voltage fed back to control the output power.

The motor design may be modified, as shown in Fig. 12b, to eliminate the mechanical commutator which is a source of wear and sparking. In the brushless DC motor, the magnets are situated on the rotor, and the armature windings, now located on the stator, are energized in an appropriate sequence by means of power electronics. Electronically commutated motors are reliable and they are particularly suited to high-speed operation,  $\omega > 30$  c/s ( $> 1000$  rpm). Position sensors form an integral part of the device since the winding to be energized depends on the position of the rotor.

One limitation is the maximum working temperature of high remanence grades of Nd–Fe–B and ferrite which cannot match the running temperatures of many classical induction motors (Table 4). For special applications, this problem can be solved by using new, high-temperature grades of Sm–Co [3]

By unrolling the armature, a linear motor is obtained. Flattening the rotor into a disk produces a pancake motor. The low moment of inertia means that high angular accelerations are possible, especially when Nd–Fe–B is used for the magnets. They may be embedded in the rotor so as to concentrate the air-gap flux.

A stepping motor turns through a fixed angle when one of the windings is energized by a suitable electronic control circuit. Designs may incorporate a ring magnet with many poles around the circumference. These can be fabricated from polymer-bonded ferrite by injection moulding and they are then pulse-magnetized using a special fixture. A common design of hybrid permanent-magnet stepper motor makes 200 steps per revolution, a  $1.8^\circ$  step size. With suitable control, it will proceed in half-steps of  $0.9^\circ$ . Tiny two-pole stepper motors using bonded Sm–Co magnets are used in clocks and watches.

## 2.6. Miscellaneous

A host of magnetic water treatment devices are marketed throughout the world for domestic and industrial use which serve to inhibit limescale deposits in pipework carrying hard water. They appear to influence the structure and morphology of the calcium carbonate precipitate, altering the calcite:aragonite ratio or the manner of calcite nucleation [21–23]. Other reports exist of a magnetic field effect on precipitation of inorganic

salts from supersaturated solution [24], the rate of electrodeposition of metals [25] and electropolymerization [26]. Permanent magnet devices are used extensively in the Chinese oil industry to control wax formation from heavy crude oil [27]. The reality of some of these effects seems to be in little doubt, but a convincing theory or explanation is often lacking. If these processes were properly understood, it may be possible to rationally design new permanent magnet devices for maximum effect in a range of industrial processes.

### 3. Conclusions

The burgeoning range of permanent magnet applications in electrical engineering has been made possible by the discovery of new magnetic materials and their continual improvement. We are near the end of the exponential growth of energy product of conventional magnets. Although a further doubling of  $(BH)_{\max}$  to  $800 \text{ kJ m}^{-3}$  might be possible in due course, further progress is constrained by the intrinsic magnetic properties of any material known to order magnetically at room temperature. Superconducting permanent magnets may find a use in future for niche applications.

There is no prospect of permanent magnet applications stagnating in future. The utility of modern permanent magnets has barely begun to be appreciated. There are good prospects for innovative applications, especially if the properties of cost-effective magnet grades can be tailored to new requirements such as thermal stability or high-temperature operation. One prediction is that the electromagnet is technically obsolete, and likely to be superseded for many purposes by permanent magnet variable flux sources which have great advantages of compactness and independence of large power supplies or cooling requirements.

Products like cordless electric tools or personal stereos owe their existence to advanced permanent magnets. One may expect that other new consumer products will appear which exploit their benefits. The fact that such a large proportion of the rare-

earth magnet market depends on a single application, miniature voice-coil actuators for hard-disc drives, suggests not so much that the market is vulnerable to changes in the shape of personal computers and home electronics as that it is capable of great expansion as a few more mass applications emerge. The electric automobile is one of the products which could transform the scale of industrial applications of permanent magnets.

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