

MAGNET DESIGN DATA

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MAGNET HANDLING INSTRUCTIONS

Safety Considerations

For safe magnet use, please follow the handling instructions detailed below. Erroneous handling may lead to function troubles and/or accidents.

Please read the product manual, including the product catalog or technical reference material, before use.

WARNINGS

- It is very dangerous for individuals equipped with electronic medical devices, such as pacemakers, or for other electronic medical devices to approach magnets. Subsequent faulty operation may lead to human damage.
- Do not swallow the magnet. If a magnet has been swallowed, contact your doctor immediately. Always keep magnets out of the reach of children.

CAUTIONS

Note: In order to avoid injury and function trouble, please follow the handling instructions below.

Design

- In general, heating a magnet results in a decrease in magnetization. Please refer to temperature characteristics displayed in catalogs and so on during assembly, so as to avoid usage outside the temperature range.
- The characteristic values listed in the catalog do not constitute guaranteed operational values. The characteristic values may not be obtained as claimed depending on the size of the magnet. Make sure to confirm these values using a similar sample prior to designing a product.
- Certain ferrite magnets display decreases in magnetism for decreases in temperature. Please refer catalogs and so on for material temperature characteristics.
- When magnetizing a magnet, trouble may occur if the magnetic field size or magnetization methods are inappropriate, leading to different characteristics than planned in the design. Please contact us for details.
- Do not store in highly corrosive gas atmosphere and high conductivity (including electrolyte, such as water) environments, hydrogen atmospheres, acid, alkaline or organic solvents, as this will lead to magnet corrosion and deterioration of characteristics and strengths(excluding Ferrite magnets). Please refer to catalogs and so on for weather and temperature resistance. Contact us for more details.
- Processing magnets may lead to magnet deterioration and failure to magnetize. Please contact us with processing details. Also beware of chipping and cracking during processing or use.
- Magnets are characteristically hard and brittle, and are therefore prone to cracking and dropout when vibrations or shocks are applied. Ensure that the design prevents cracking and dropout.
- Use of magnets in high-speed revolving bodies, such as motors, may lead to magnet damage. Ensure that the design prevents fragment shatter in the case of damage.
- Depending on process conditions, the magnet or counterpart material may break when applying processes, such as during presses. Ensure that design conditions prevent such breakage.
- When using adhesives to join magnets with magnets, yokes, or pole yokes, always ensure the reliability of adhesive type, volume, conditions, strength, and so on.

CAUTIONS

Note: In order to avoid injury and function trouble, please follow the handling instructions below.

Assembly/Handling

- Handle magnetized magnets carefully as these display strong attraction power. Inserting hands or fingers in the space between the magnet and magnetic bodies, such as magnets, metal fragments, knives, scissors and so on, may lead to unpredictably serious injury. Large shocks may lead to magnet break and shatter due to the strong magnetic attraction, and fragments may enter the eye.
- Beware of sharp magnet edges, as these may lead to hand and finger injury.
- When magnetizing with air-core coils, ensure that the magnet is fixed for safety reasons, as the magnet may eject violently from the coil.
- Ensure the magnetized magnet is used in the correct usage environment, as magnets attract dust, such as metal powder and magnetic fragments. In some cases, the magnet may need to be washed after assembly.
- When bonding a magnet, ensure that the bonding surface is free of oil, impurities and so on as adhesive strength may decrease and dropout may occur.

Storage

- Store in locations free from shocks, such as when dropped, as this may lead to chipping and breakage.
- Do not store in locations prone to rainwater, dust or condensation, as this may lead to changes in surface conditions, physical properties and magnetic characteristics.

Others

- Do not place magnets near floppy disks, magnetic cards, magnetic tape, prepaid cards, tickets or cathode ray tubes. Placing magnets near magnetic recorded media may result in damage to records.
- Do not place magnets near electronic devices. Trouble and/or accidents may result due to magnetic effects on instruments and controller circuits.
- Individuals with allergic predispositions towards metallic objects should refrain from touching magnets. Contact with magnets may lead to skin reactions and redness.
- Never swallow liquids that have come into contact with magnets or liquids resulting from licking magnets.

Special conditions for rare-earth magnets

- Rare-earth magnet alloy powder is designated as Class 2 (flammable solids) or Class 1 hazardous material by the Fire Defense Law. Please handle according to appropriate regulations. Ensure that magnet friction during use does not produce powder, as fine powder is highly prone to ignition.
- When processing the raw material used for cutout, please obey the following items regarding powder resulting from cutting. The powder may be prone to spontaneous ignition.
 - (1) Do not place near naked fire, inflammable materials or organic solvents.
 - (2) Do not vacuum powder using an electric vacuum cleaner.
 - (3) Always keep a powder fire extinguisher, sand, and so on for use in the event of a fire.
 - (4) Ensure that powder resulting from grinding and cutting is not released into the air and that it is stored in a water-filled container, below the water level. Please contact us regarding post-storage procedures.

Note to customers

Please consult our relevant departments at length for magnetic product use. Also, please contact us before you make any change to their application or method of installation after you have begun using them.

Ensure that design and usage methods prevent the occurrence of safety-related trouble.

BASIC CHARACTERISTICS

1. PHYSICAL AND MECHANICAL CHARACTERISTICS

Magnets are hard ceramic magnets of finely joined crystal grains created by solid state reaction. Although the environmental characteristics are excellent, the resulting mechanical strength is only 0.5 to 0.9×10^8 N/m² (5 to 9kgf/mm²).

In other words, special care needs to be taken when handling, as these magnets are easily broken by dropping on a hard floor or impacts between magnets. With regard to the shape, the magnets must be designed with care so as to chipping or breaking is kept to an absolute minimum on corners and edges that are easily broken (for details, please refer to each material).

2. TEMPERATURE CHARACTERISTICS

2-1. Temperature change and movement of knee points

When considering the magnetic characteristics, temperature is an important factor. For the residual magnetic flux density B_r of TDK's ferrite magnets, the temperature coefficient $\Delta B_r / B_r / \Delta T$ shows negative characteristics of $-0.18\%/K$ ($\%/^{\circ}C$), and the coercive force H_{cJ} shows positive characteristics of $+0.3$ to $0.5\%/K$ ($\%/^{\circ}C$).

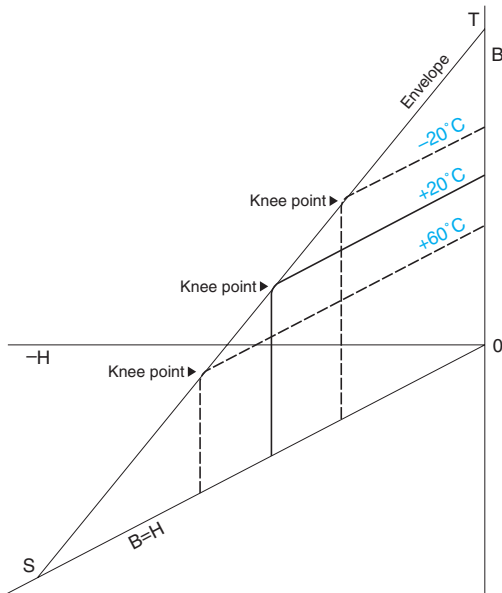


Fig. 1 Temperature change and movement of knee points

As shown in figure 1, when the coercive force H_{cJ} of the ferrite magnet is small, the knee point appears in the second quadrant of the B-H curve (the point at which the magnetic flux density (B) drops suddenly).

However, the position of the knee point will change depending on the change in temperature. For example, when the temperature decreases the knee point gradually moves toward the top right corner as B_r increased and as H_{cJ} decreases.

2-2. Reversible and irreversible demagnetization loss (Irreversible low temperature demagnetization)

The demagnetization phenomenon due to temperature change should be considered when designing magnetic circuits which contain ferrite magnets.

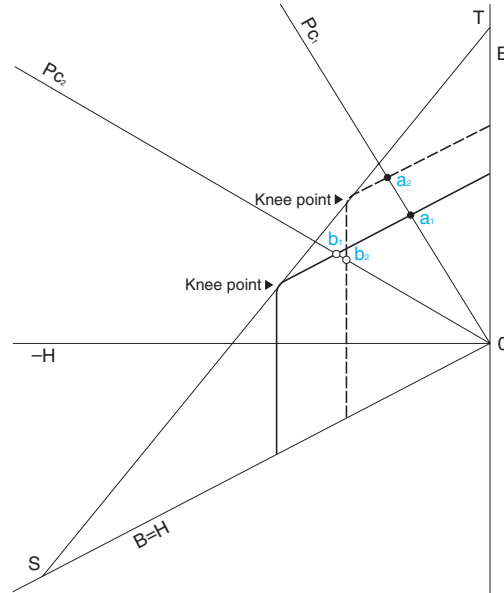


Fig. 2 Reversible and irreversible change of the operating points

In figure 2, the intersection of the permeance coefficient line P_{c1} with the solid B-H curve at normal temperature defines the operating point a_1 which is sufficiently in a higher position than the knee point of B-H curve. When the temperature decreases, the B-H curve changes to the dotted line where the operating point shifts to a_2 . Because the slope of the permeance coefficient line P_{c1} is sufficiently steep in this model, the operating point at the lower temperature a_2 is still in a higher position than the knee point of the dotted B-H curve. In this case, when the temperature returns to normal, the operating point returns to the original position a_1 .

This is referred to as "Reversible change".

On the contrary, if the permeance coefficient line is near the knee point (P_{c2}), as the temperature decreases, the operating point b_1 at the normal temperature is shifted to the operating point b_2 which is below the knee point of the dotted B-H curve at the lower temperature.

In this case, the operating point b_2 does not return to b_1 even when the temperature returns to normal. This is referred to as "Irreversible change", where the magnet is irreversibly demagnetized and the performance of the magnet can not be restored without re-magnetizing.

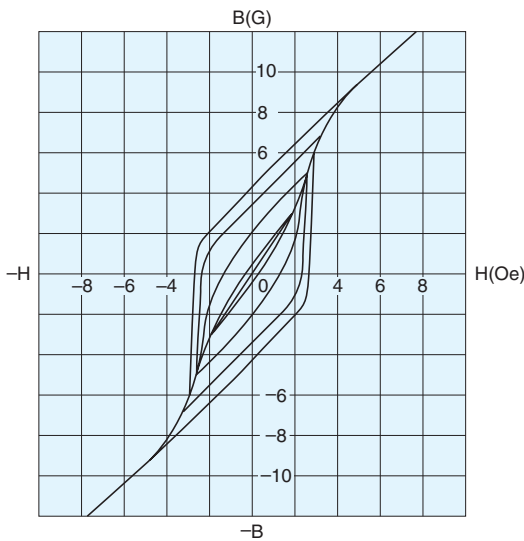
The amount of demagnetization found is described in figure 3.

If however this was to be done at the lowest operating temperature, the irreversible demagnetization will be worse. Therefore it is imperative that if the magnets are expected to be used at low temperatures and under external magnetic influence, the following precautions must be taken.

- (1) Use magnets of a high coercive force H_{cJ} , and;
- (2) Design with a higher permeance coefficient by increasing the magnet thickness and/or reducing magnet cross sectional area and/or the air gap.

4. MAGNETIZATION CHARACTERISTICS

The magnet will have lower residual flux density B_r and lower intrinsic coercive force H_{cJ} , it is not fully magnetized. This will cause the magnet to have characteristics difference from those shown for a saturated magnet (Please refer to figure 5).

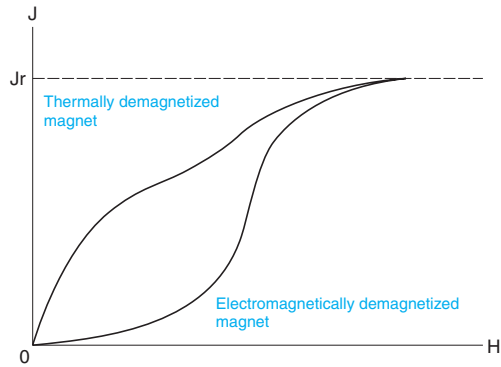


As shown by the four loops (minor hysteresis loops), when the strength of the magnetic field is insufficient, the magnet is not magnetized at the saturated level, and the residual flux density and coercive force only reach the value corresponding to the strength of the magnetic field applied.

Fig. 5 Relationship between magnetizing field force and the residual flux density and coercive force

The magnetic characteristics but also the shape of the ferrite magnet do not only determine the required magnetization field for the use of magnets.

Also the method of demagnetization, if conducted on ferrite magnets, influences the necessary saturation field as shown in figure 6.



The magnetization characteristics are difference for a ferrite magnet that is demagnetized thermally and electromagnetically.

When a magnet is demagnetized thermally (heated above the Curie temperature), the magnetization curve rises comparatively quicker. The induced flux density in the magnet increases faster for the same applied field than for a magnet that was demagnetized electromagnetically. To have most suitable magnetization characteristics, it is necessary to consider the different demagnetization properties of the both.

Fig. 6 Saturation characteristics of ferrite based on demagnetization method

Generally, by applying a magnetizing field that is three times the level of H_{cJ} one can reach the saturation point. However testing should be conducted to ensure adequate magnetization has been achieved.

Figure 7 shows the magnetization characteristics of TDK ferrite magnets in the first quadrant.

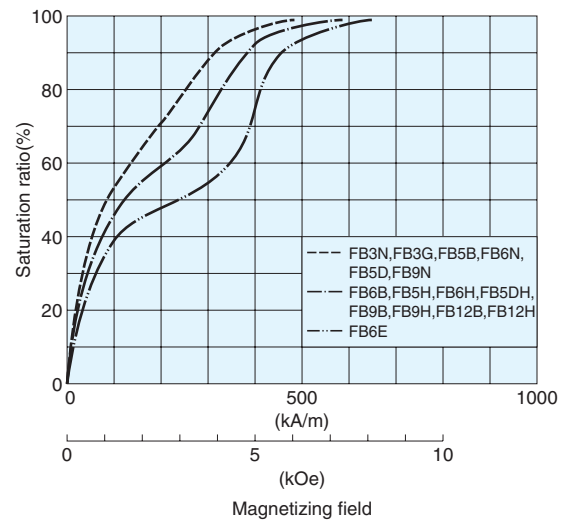


Fig. 7 First quadrant magnetization characteristics of TDK ferrite magnet

MEASURING MAGNETIC CHARACTERISTICS/MAGNETIC CIRCUIT DESIGN

In order to make calculation formulas simple, the CGS units are applied in the following data. Converting to SI units, please refer to "THE UNITS CONVERSION TABLE" shown in the following description.

1. MEASUREMENT METHOD

1-1. Measurement of B-H characteristics

Certain magnetic test equipment is required to measure the fundamental characteristic of a magnet including residual flux density B_r , coercive force H_{cB} , intrinsic coercive force H_{cJ} and maximum energy product $(BH)_{max}$.

This equipment includes; a gauss meter, flux meter, X-Y recorder, electromagnet and a sample that allows no air gap in the circuit when it is inserted between the electromagnet pole-pieces. To eliminate the air gap, a small core sample is precisely machined. It is therefore difficult to measure precisely for shapes actually used. In these situations, the following simple methods are used to measure magnet properties (Please refer to figure 1).

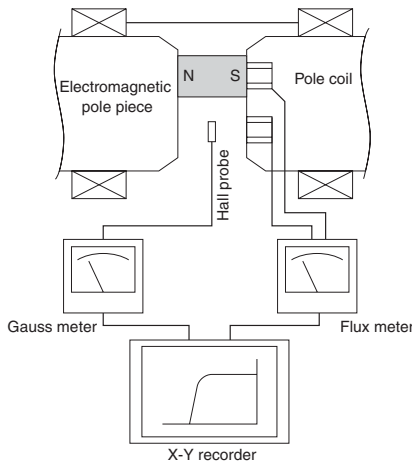


Fig. 1 Measurement of B-H characteristics

1-2. Simple measurement method for a typical magnet

The simple measurement method shown in below uses a gauss meter with probe and a flux meter with a search coil. A good practice is to make a standard magnet for calibration and adjustment to establish consistency in the test over time.

1-2-a. Measurement method of flux density B

A gauss meter is generally used with a semiconductor hall element to measure the surface flux density and the magnetic flux density at some points (Please refer to figure 2).

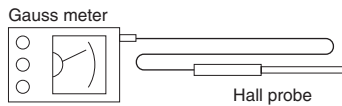
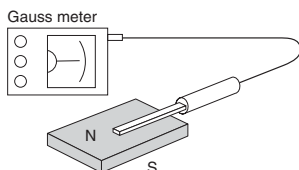
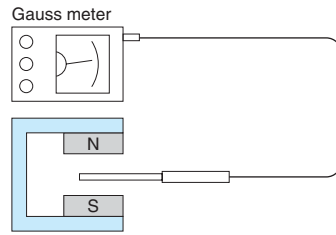


Fig. 2

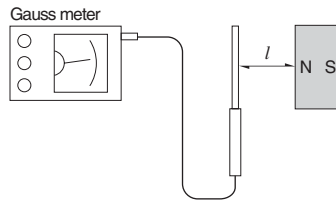
(1) Surface flux density measurement method (This method is used in most cases.)



(2) Measurement method of center flux density



(3) Measurement method at some distance from the magnet surface in an open circuit.



1-2-b. Measurement method of flux

When measuring flux, flux-meter and search coils are regularly used (Please refer to figure 3).

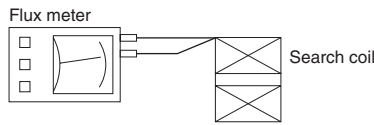
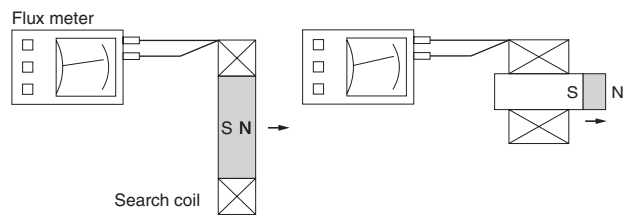
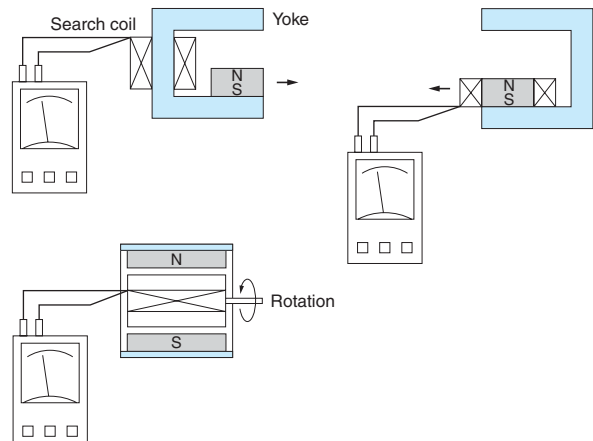


Fig. 3

(1) Open flux method



(2) Measurement method used for magnetic circuits



2. MAGNETIC CIRCUIT ANALYSIS

2-1. Basic calculation method

The basic calculation method of a magnetic circuit is the same as is used in a basic electrical analysis using Ohm's Law.

The total magnetic flux ϕ (analogous to electric current), magnetomotive force F (analogous to voltage), and magnetic reluctance R (analogous to electrical resistance) are related as shown in below.

$$\text{Total magnetic flux } \phi = \frac{\text{Magnetomotive force } F}{\text{Magnetic reluctance } R} \dots\dots\dots(1)$$

In magnetic circuit calculations, it is more common to use the magnetic permeance P , which is the reciprocal to reluctance R . Using permeance instead of reluctance, the total flux equation is changed as shown in below.

$$\begin{aligned} \text{Total magnetic flux } \phi \\ = \text{Magnetomotive force } F \cdot \text{Permeance } P \dots\dots\dots(2) \end{aligned}$$

The permeance P is a function of the magnetic circuit length L , magnetic circuit cross sectional area A , and magnetic permeability μ .

$$\text{Permeance } P = \frac{\text{Permeability } \mu \cdot \text{Cross sectional area } A}{\text{Magnetic circuit length } L} \dots\dots\dots(3)$$

This means that when the length is shorter and the magnet area and permeability are greater, the permeance is greater. Conversely the reluctance is reduced.

The total magnetic circuit permeance P_t is considered as a total of any air gap permeance P_g defined as a reciprocal of magnetic reluctance in the air gap, and the sum of leakage permeance P_f , defined as the reciprocal of the magnetic reluctance of the leakage flux paths at the poles.

$$P_t = P_g + P_f = P_g + P_{f1} + P_{f2} + \dots\dots\dots + P_{fn} \dots\dots\dots(4)$$

2-2. Magnetomotive force loss coefficient f

The magnetomotive force loss coefficient f is the ratio of the total magnetomotive force F_t and the magnetomotive force in the air gap F_g for a given magnetic circuit.

$$\text{Magnetomotive force loss coefficient } f = \frac{F_t}{F_g} \dots\dots\dots(5)$$

The total magnetomotive force F_t in the magnetic circuit is determined as the product of the magnetic field strength H_d at the operating point, and the length of the magnet L_m .

The magnetomotive force in the air gap F_g is given as the product of the magnetic field strength of the air gap $H_g (=B_g)$, and the length of the air gap L_g .

Thus equation (5) becomes as follows.

$$\begin{aligned} \text{Magnetomotive force loss coefficient } f \\ = \frac{H_d \cdot L_m}{H_g \cdot L_g} = \frac{H_d \cdot L_m}{B_g \cdot L_g} \dots\dots\dots(6) \end{aligned}$$

2-3. Leakage coefficient σ

The leakage coefficient is the ratio of the total magnetic flux ϕ_t generated from the magnet in a given circuit and the flux found in the air gap ϕ_g .

$$\text{Leakage coefficient } \sigma = \frac{\phi_t}{\phi_g} \dots\dots\dots(7)$$

The total magnetic flux generated in a magnet ϕ_t is given as the accumulation of flux density at the operating point B_d over the cross sectional area of the magnet A_m .

And the magnetic flux in the air gap ϕ_g is given as the accumulation of flux density B_g over the area of the air gap A_g .

Equation (7) now becomes:

$$\text{Leakage coefficient } \sigma = \frac{B_d \cdot A_m}{B_g \cdot A_g} \dots\dots\dots(8)$$

From equation (2), we can rewrite equation (7) as follows:

$$\text{Leakage coefficient } \sigma = \frac{F_t \cdot P_t}{F_g \cdot P_g} \dots\dots\dots(9)$$

Generally the magnetomotive force loss coefficient f is approximately 1, so equation (9) becomes:

$$\text{Leakage coefficient } \sigma \doteq \frac{P_g + P_f}{P_g} = 1 + \frac{P_f}{P_g}$$

Splitting P_f in each part of the magnetic leakage path, the leakage coefficient σ can be written as equation (10).

$$\text{Leakage coefficient } \sigma \doteq 1 + \frac{P_{f1} + P_{f2} + \dots\dots\dots P_{fn}}{P_g} \dots\dots\dots(10)$$

2-4. Permeance coefficient P_c

The permeance coefficient is used to design a permanent magnet application with a B-H curve. This is defined as the ratio of flux density B_d and magnetic field strength H_d of the operating point, and equation (11) becomes:

$$\text{Permeance coefficient } P_c = \frac{B_d}{H_d} \dots\dots\dots(11)$$

The relationship is shown in figure 1 below:

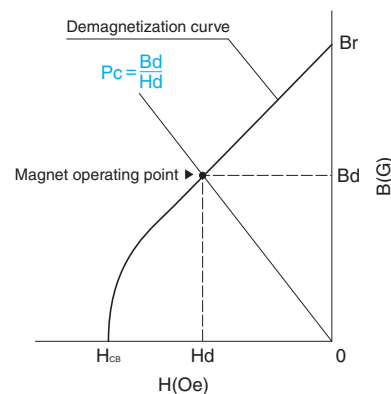


Fig. 1

• In order to make calculation formulas simple, the CGS units are applied in this section. If you need to convert the value in SI units, please refer to "Conversion Table of SI and CGS units".

• All specifications are subject to change without notice.

2-4-a. Permeance coefficient in a magnetic circuit

The permeance coefficient in a magnetic circuit can be rewritten from equations (6) and (8), and then they are placed back into equation (11).

Equation (6) therefore,

$$Hd = \frac{Bg \cdot Lg}{Lm} f \dots\dots\dots(12)$$

Equation (8) therefore,

$$Bd = \frac{Bg \cdot Ag}{Am} \sigma \dots\dots\dots(13)$$

Then,

$$Pc = \frac{Lm \cdot Ag}{Am \cdot Lg} \cdot \frac{\sigma}{f} \dots\dots\dots(14)$$

2-4-b. Permeance coefficient of a magnet in an open circuit

When a magnet is used in an open circuit, the permeance coefficient is greatly affected by the magnet shape. Therefore it is extremely difficult to calculate the exact value.

The following figures of the cylindrical type magnet (the relationship graph of the dimension ratio and permeance coefficient) can be used to approximate the permeance.

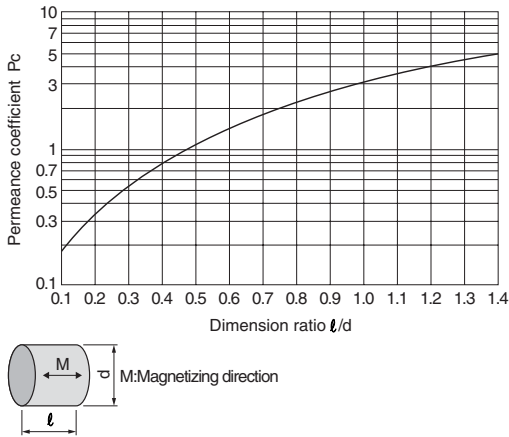


Fig. 2

The approximate equation is as follows:

$$Pc = 1.35 \left(\frac{l}{d} \right) \left[\sqrt{1 + \left(\frac{l}{d} \right)^2} + \left(\frac{l}{d} \right) \right] \dots\dots\dots(15)$$

2-5. Calculation of necessary magnet length Lm, cross sectional area Am and volume Vm

Equation (6) therefore,

$$Lm = \frac{Bg \cdot Lg}{Hd} f \dots\dots\dots(16)$$

Equation (8) therefore,

$$Am = \frac{Bg \cdot Ag}{Bd} \sigma \dots\dots\dots(17)$$

If Hd, Bd, Ag, Lg, f and σ are provided, Lm and Am can be found using equations (16) and (17). The required magnet volume Vm is calculated as follows:

$$Vm = Am \cdot Lm = \frac{Bg^2 \cdot Ag \cdot Lg \cdot \sigma \cdot f}{Bd \cdot Hd} \dots\dots\dots(18)$$

The necessary magnet volume is inversely proportional to the energy product at a particular operating point.

• In order to make calculation formulas simple, the CGS units are applied in this section. If you need to convert the value in SI units, please refer to "Conversion Table of SI and CGS units".

• All specifications are subject to change without notice.

2-6. Method to determine the leakage coefficient σ , and magnetomotive force loss coefficient f

2-6-a. Experimental method

With a search coil

1. A search coil was winding around the magnet to measure the gap flux.
2. Bd is calculated from total flux ϕ_g /magnet sectional area Am.
3. Determine Hd using the B-H demagnetization curve.
4. Measure Bg, Ag, Lg, Am and Lm.
5. Calculate f and σ using equations (6) and (8).

Without a search coil

1. Hypothesize f (generally 1.0 to 1.2).
2. Measure Lm, Bg and Lg.
3. Calculate Hd is using equation (12).
4. Determine Bd from the B-H demagnetization curve.
5. Measure Am and Ag, and calculate σ using equation(8).

2-6-b. Calculating leakage coefficient σ

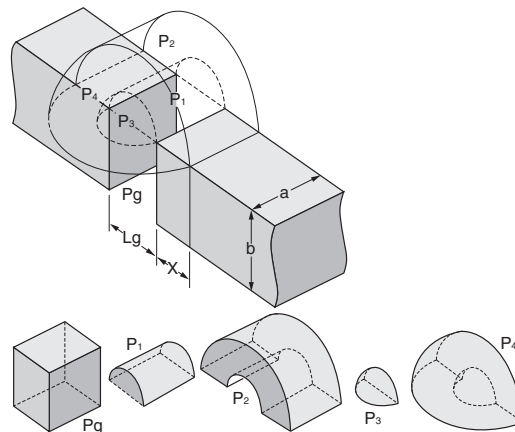
The leakage coefficient is calculated as follows:

Determine Pg and Pf1 to Pfn by calculation (refer to the example shown in below) and calculate σ using equation (10).

$$\text{Equation (10): } \sigma \doteq 1 + \frac{Pf_1 + Pf_2 + \dots + Pfn}{Pg}$$

(Example)

An example of the calculated permeance for a magnetic circuit is shown in below.



1. Permeance of the space gap

$$Pg = \mu_0 \frac{a \cdot b}{Lg}$$

2. Permeance of half cylinder portion

$$P1 = 0.264\mu_0 \cdot a$$

3. Permeance of the hollow half cylinder portion

$$P2 \approx \frac{0.64\mu_0 \cdot a}{(Lg/x+1)} \text{ or } P2 = \frac{\mu_0 \cdot a}{\pi} \ln\left(1 + \frac{2X}{Lg}\right) \quad [Lg < 3x]$$

4. Permeance of the quadsphere portion

$$P3 = 0.077\mu_0 \cdot Lg$$

5. Permeance of the hollow quadsphere portion

$$P4 = \frac{\mu_0 \cdot x}{4}$$

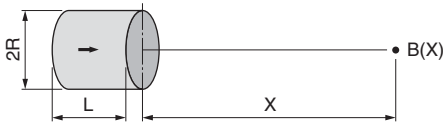
By combining the permeance of these respective portions, the approximate leakage coefficient in the circuit can be found with using equation (10).

3. EQUATION BY DETERMINING THE MAGNETIC FLUX DENSITY AT A DISTANCE X FROM THE MAGNET AT THE CENTER LINE, B(X)

When the operating point Bd is above the knee point of the B-H curve, the magnetic field distribution on the outside of the magnet, assuming the space of length X and the same cross section shape with permeability equal to the magnet, is similar to the magnetic field generated by the closed circuit current on the outer surface.

The equations for three typical magnet shapes and some applications are shown in below. (These formulas can be used for ferrite or rare earth magnets.)

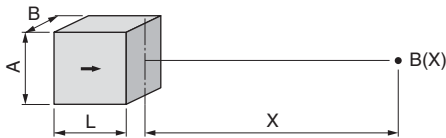
3-1. Cylindrical shaped



$$B(X) = \frac{Br}{2} \left[\frac{L+X}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}} \right]$$

Br: Residual flux density of the magnet
X: Distance from the surface of the magnet

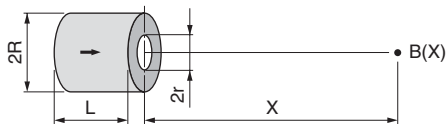
3-2. Block shaped



$$B(X) = \frac{Br}{\pi} \left[\tan^{-1} \frac{AB}{2X\sqrt{4X^2+A^2+B^2}} - \tan^{-1} \frac{AB}{2(L+X)\sqrt{4(L+X)^2+A^2+B^2}} \right]$$

Br: Residual flux density of the magnet
X: Distance from the surface of the magnet
The angle is radian.

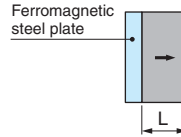
3-3. Ring shaped



$$B(X) = \frac{Br}{2} \left[\left(\frac{L+X}{\sqrt{R^2+(L+X)^2}} - \frac{L+X}{\sqrt{r^2+(L+X)^2}} \right) - \left(\frac{X}{\sqrt{R^2+X^2}} - \frac{X}{\sqrt{r^2+X^2}} \right) \right]$$

Br: Residual flux density of the magnet
X: Distance from the surface of the magnet

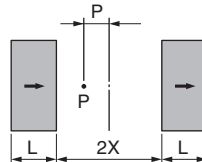
3-4. Ferromagnetic steel plate on the back of the magnet



The steel plate must have sufficient thickness that will be not to become saturated.

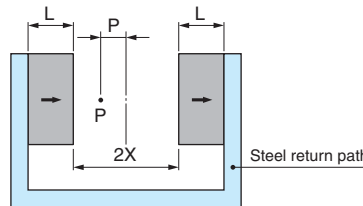
Substitute $2L$ for L in equations of 3-1, 3-2 and 3-3 above.

3-5. Calculating B(X) of same shaped two magnets when spaced at a distance of 2X



If two magnets are used as shown in above, $B(X)$ at the center of the air gap is doubled based on equations 3-1, 3-2 and 3-3. The $B(X)$ at point P in the air gap is found using the same equations as above, except the sum of $B(X-P)$ and $B(X+P)$, where $X+P$ and $X-P$ are substituted into the equations for X .

3-6. Same shaped two magnets with a steel return path



Substitute $2L$ for L in the equations derived in the above 3-5.

• In order to make calculation formulas simple, the CGS units are applied in this section. If you need to convert the value in SI units, please refer to "Conversion Table of SI and CGS units".

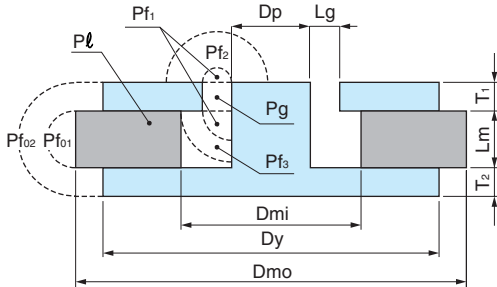
• All specifications are subject to change without notice.

4. CALCULATING THE AIR GAP FLUX DENSITY FOR A LOUD-SPEAKER MAGNETIC CIRCUIT

4-1. Calculation method for outer magnet type

Assume the permeance can be found based on the leakage flux path shown in the figure below.

The gap permeance P_g and the leakage permeance P_f in each part can be found as follows.



D_p : Center pole diameter
 T_1 : Top plate thickness
 D_{mo} : Outside radius of magnet
 L_m : Magnet thickness
 A_g : Gap cross sectional area
 D_y : Plate diameter
 T_2 : Bottom plate thickness
 D_{mi} : Inside radius of magnet
 L_g : Gap length

$$P_g = \mu_0 A_g / L_g = \pi \mu_0 (D_p + L_g) T_1 / L_g$$

$$P_{f1} = 0.264 \pi \mu_0 (D_p + L_g)$$

$$P_{f2} = \mu_0 (D_p + L_g) \ell n(1 + D_p / L_g)$$

$$P_{f3} = 2 \mu_0 (D_p + L_g) \ell n\{1 + (D_{mi} - D_p - 2L_g) / L_g\}$$

$$P_{f01} \doteq \mu_0 0.264 \pi \cdot D_{mo} + 0.308 L_m$$

$$P_{f02} \doteq \mu_0 D_{mo} \cdot \ell n\{1 + (T_1 + T_2) / L_m\} + (T_1 + T_2)$$

$$P_\ell = \pi \mu_0 \sqrt{(D_{mo} + D_{mi}) L_m} / 2$$

We can calculate the total permeance P_t of the whole circuit from the equations shown in above.

$$P_t = P_g + 3P_{f1} + P_{f2} + P_{f3} + P_{f01} + P_{f02} + P_\ell$$

From the previous equation, we can derive an equation for the leakage coefficient.

$$\sigma = P_t / P_g$$

Then,

$$P_c = \frac{L_m}{A_m} \cdot P_g \cdot \frac{\sigma}{f} = \frac{L_m}{A_m} \cdot \frac{P_t}{f}$$

A_m : Cross sectional area of magnet
 f : Magnetomotive loss coefficient $\doteq 1.1$

The flux density at the magnet operating point, B_d :

$$B_d = \frac{B_r}{1 + \mu_{rec} / P_c}$$

μ_{rec} : Recoil permeability $\doteq 1.7$

The air gap magnetic flux density, B_g :

$$B_g = \frac{A_m \cdot B_d}{A_g} \cdot \frac{1}{\sigma}$$

The bottom plate must have sufficient thickness T_2 not to become saturated. This is determined as follows:

The leakage coefficient as viewed from the bottom plate is:

$$\sigma_p = (P_g + 3P_{f1} + P_{f2} + P_{f3}) / P_g$$

The total magnetic flux passing through the bottom plate is:

$$\phi_p = B_g \cdot A_g \cdot \sigma_p$$

Assuming the saturated flux density of the bottom plate is 15kG, the thickness of the bottom plate T_2 should be:

$$15000 \pi \cdot D_p \cdot T_2 \geq \phi_p$$

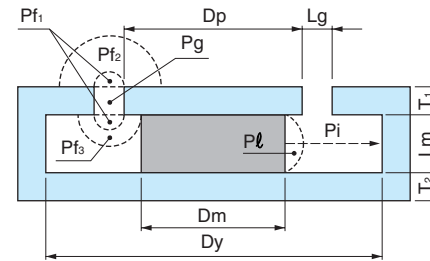
Then,

$$T_2 \geq \phi_p / 15000 \pi \cdot D_p$$

4-2. Calculation method for inner magnet type

Assume the permeance can be found based on the flux leakage path shown in figure below in the same way as for the outer magnet type.

The gap permeance P_g and the leakage permeance P_f in each part can be found as follows:



D_p : Center pole diameter
 T_1 : Top plate thickness
 D_m : Diameter of magnet
 A_g : Gap cross sectional area
 D_y : Inside plate diameter
 T_2 : Bottom plate thickness
 L_m : Magnet thickness
 L_g : Gap length

$$P_g = \mu_0 A_g / L_g = \pi \mu_0 (D_p + L_g) T_1 / L_g$$

$$P_{f1} = 0.264 \pi \mu_0 (D_p + L_g)$$

$$P_{f2} = \mu_0 (D_p + L_g) \ell n(1 + D_p / L_g)$$

$$P_{f3} = \mu_0 (D_p + L_g) \ell n\{1 + (D_p - D_m) / L_g\}$$

$$P_\ell = \pi \mu_0 \sqrt{D_m \cdot L_m} / 2 \quad [P_\ell > P_i]$$

or

$$P_i = \pi \mu_0 L_m (D_m + D_y) / 4 (D_y - D_m) \quad [P_i > P_\ell]$$

Then the total permeance P_t is:

$$P_t = P_g + 2P_{f1} + P_{f2} + P_{f3} + P'$$

P' is P_ℓ or P_i , whichever is larger.

The calculation process of the leakage coefficient σ , permeance coefficient P_c , flux density at the operating point B_d , and air gap flux density B_g is the same as was shown for the outer magnet type.

The plate thickness T_1 and T_2 required for the plate not to become saturated is shown in below, and the calculation process is the same as for the outer magnet type.

The leakage coefficient is:

$$\sigma_p = (P_g + 2P_{f1} + P_{f2} + P_{f3} + P_\ell \text{ or } P_i) / P_g$$

The total magnetic flux ϕ_p through the plate is:

$$\phi_p = B_g \cdot A_g \cdot \sigma_p$$

Assuming the saturated flux density of the plate is 15kG, T_1 and T_2 should be:

$$T_1, T_2 \geq \phi_p / 15000 \pi \cdot D_m$$

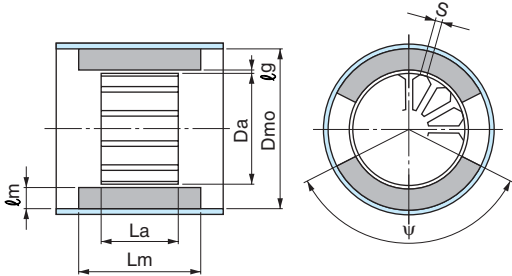
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5. CALCULATION OF THE EFFECTIVE MAGNETIC FLUX IN A MOTOR

There are many variables that change the magnetic circuit of a motor greatly, such as the number of rotor slots, slot geometry, motor housing thickness, etc.

Therefore the following calculation shows only the basic concepts



Dmo: Outside radius of magnet
Lm: Magnet axial length
 ψ : Magnet angle (radians)
 l_m : Magnet pole thickness

Da: Armature diameter
La: Armature length
S: Slot width
 l_g : Air gap length

1) Cross sectional area A_m of the magnet is as follows:

$$A_m = \frac{1}{2} \psi L_m (D_{mo} - l_m) = \frac{1}{2P} \alpha_i \pi L_m (D_{mo} - l_m)$$

$\alpha_i = p \psi / \pi$: An arcuate of a pole, P: The binary number of poles

2) Magnet equivalent value shape ratio l/d

$$\frac{l}{d} = \frac{l_m}{\sqrt{4A_m/\pi}}$$

3) Leakage permeance coefficient P_i and P_L

• Permeance coefficient of the magnet alone P_i

$$P_i = \zeta \left(\frac{l}{d} \right) \left[\sqrt{1 + \left(\frac{l}{d} \right)^2} + \frac{l}{d} \right]; \zeta = \frac{1}{5} (12 - p)$$

• Permeance coefficient of the magnet alone (including the yoke) P_L

$$P_L = \xi \left(\frac{2l}{d} \right) \left[\sqrt{1 + \left(\frac{2l}{d} \right)^2} + \frac{2l}{d} \right]; \xi = 1.3 \sim 1.4$$

4) Carter coefficient k_c

$$k_c = \frac{t_s}{t_s - \gamma_c l_g}; \gamma_c = \frac{(S/l_g)^2}{5 + (S/l_g)}; t_s = \frac{\pi D_a}{S n}$$

Where,

t_s : tooth pitch

$S n$: Number of slots

5) Effective permeance coefficient P_u

$$P_u = \frac{l_m}{A_m} \cdot \frac{A_g}{k_c l_g}; A_g = \frac{1}{2} \psi k_i L_a (D_a + l_g); k_i \approx 0.97$$

Where,

A_g : Air gap cross sectional area

k_i : Lamination factor in the armature

6) Leakage coefficient σ

$$\sigma = 1 + P_i/P_u, \quad \sigma P_u = P_u + P_i$$

7) Magnetic flux at the pole (Effective magnetic flux) ϕ_g

$$\phi_g = 0.95 B_r \frac{A_m \cdot P_u}{\mu_{rec} + \sigma P_u}$$

Where,

μ_{rec} : Recoil permeability

The above calculation method gives no special consideration to saturation of the magnetic circuit. In reality there can be varying degrees of saturation in the motor housing and rotor.

When comparing ϕ_g calculated above with the actually measured value, if the actually measured value is smaller than the calculated value, the motor circuit can be considered to have some saturation in one or more of the components.

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CONVERSION TABLE OF SI AND CGS UNITS

View in conversion table:

If the conversion ratio at the left of ► sign is multiplied by the column of SI unit system, the value becomes in CGS system.

If the conversion ratio at the right of ◄ sign is multiplied by the column of CGS unit system, the value becomes in SI system.

Terms	Symbol	SI units		Conversion(Multiplication)		CGS units	
		Unit's name	Symbol	SI to CGS	CGS to SI	Unit's name	Symbol
Magnetic flux	ϕ	Weber	Wb	10^8 ►	◄ 10^{-8}	Maxwell	Mx
Flux density	B	Tesla	T	10^4 ►	◄ 10^{-4}	Gauss	G
Magnetic field strength	H	Ampere/meter	A/m	$4\pi \times 10^{-3}$ ►	◄ $10^3/4\pi$	Oersted	Oe
Intensity of magnetization	M	Ampere/meter	A/m	10^{-3} ►	◄ 10^3	Gauss	G
Magnetic polarization	J	Tesla	T	$10^4/4\pi$ ►	◄ $4\pi \times 10^{-4}$	Gauss	G
Magnetomotive force	Fm	Ampere	A	$4\pi \times 10^{-1}$ ►	◄ $10/4\pi$	Gilbert	Gi
Force	F	Newton	N	10^5 ►	◄ 10^{-5}	Dyne	dyn
Permeability	μ	Henry/meter	H/m	$10^7/4\pi$ ►	◄ $4\pi \times 10^{-7}$	—	
Permeability, vacuum	μ_0	$4\pi \times 10^{-7}$ Henry/meter	H/m			1	
Reluctance	Rm	1/Henry	H ⁻¹	$4\pi \times 10^{-9}$ ►	◄ $10^9/4\pi$	Gilbert/Maxwell	Gi/Mx
Permeance	P	Henry	H	$10^9/4\pi$ ►	◄ $4\pi \times 10^{-9}$	Maxwell/Gilbert	Mx/Gi
Energy product	BH	Joule/metric ³	J/m ³	$4\pi \times 10$ ►	◄ $10^{-1}/4\pi$	Gauss • Oersted	G • Oe
				10 ►	◄ 10^{-1}	erg/cm ³	erg/cm ³

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