

電磁感應(Electromagnetic Induction)

✦ 電磁感應現象

導體相對於磁場運動，導致感應電流的產生。

磁場隨時間變化，導致感應電場，進而形成感應電流。

● 產生電磁感應現象的主要實驗

磁場強度變化 (change in field strength)

線圈面積變化 (change in area)

線圈方向的改變 (change in orientation)

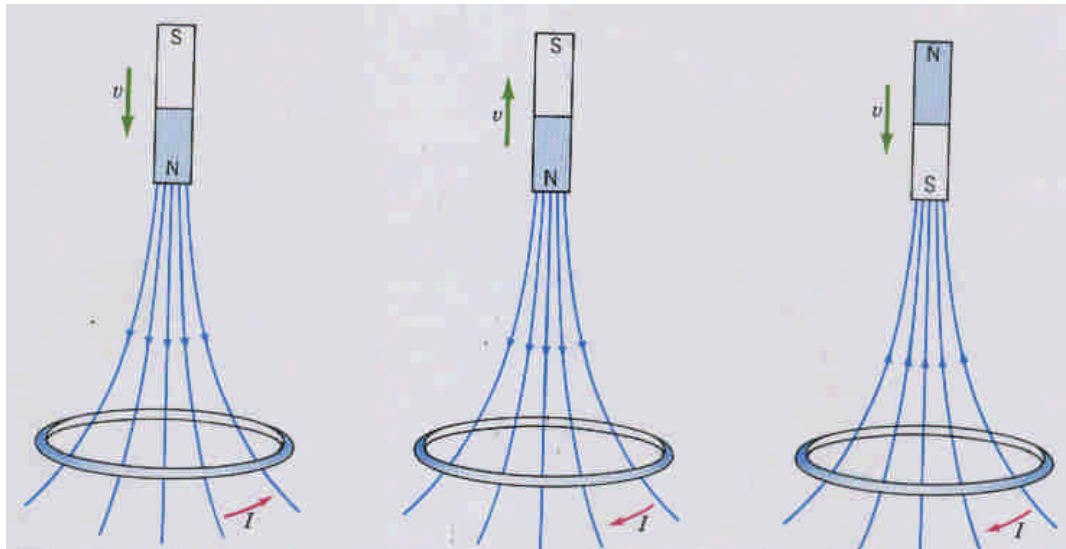


Fig.31.3

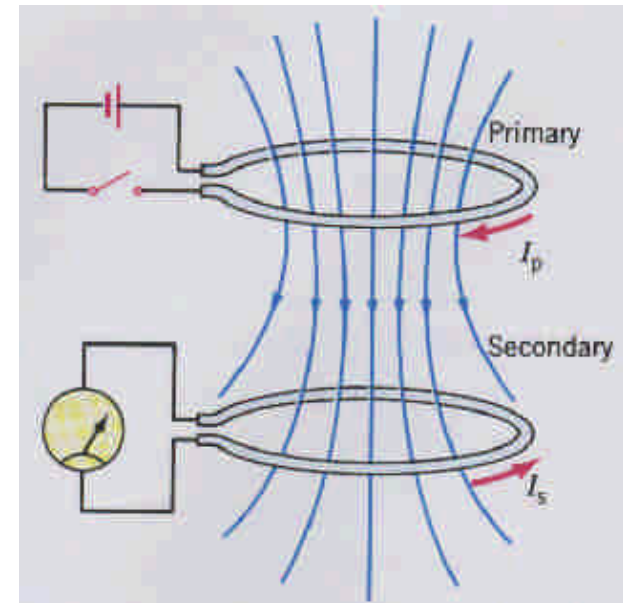


Fig.31.4

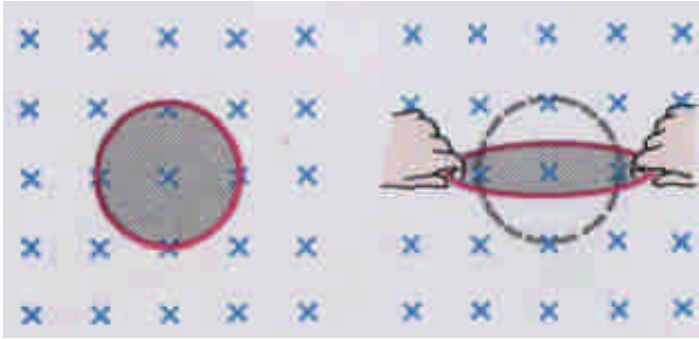


Fig.31.5

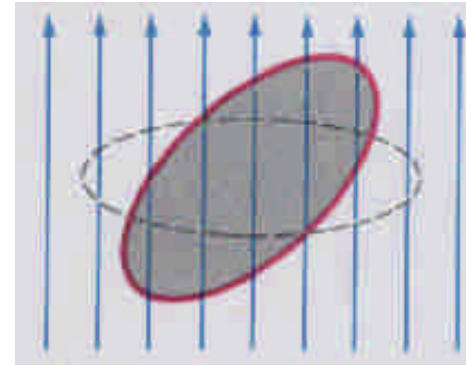


Fig.31.6

- Magnetic flux (磁通量) $\left\{ \begin{array}{l} \Phi_B = \vec{B} \cdot \vec{A} = BA \cos \theta \quad (\text{Uniform } B) \\ \Phi_B = \int \vec{B} \cdot d\vec{A} \quad (\text{nonuniform } B \text{ or the surface isn't flat}) \end{array} \right.$

The SI unit \Rightarrow weber (Wb) $\Rightarrow 1 \text{ T} = 1 \text{ Wb/m}^2$

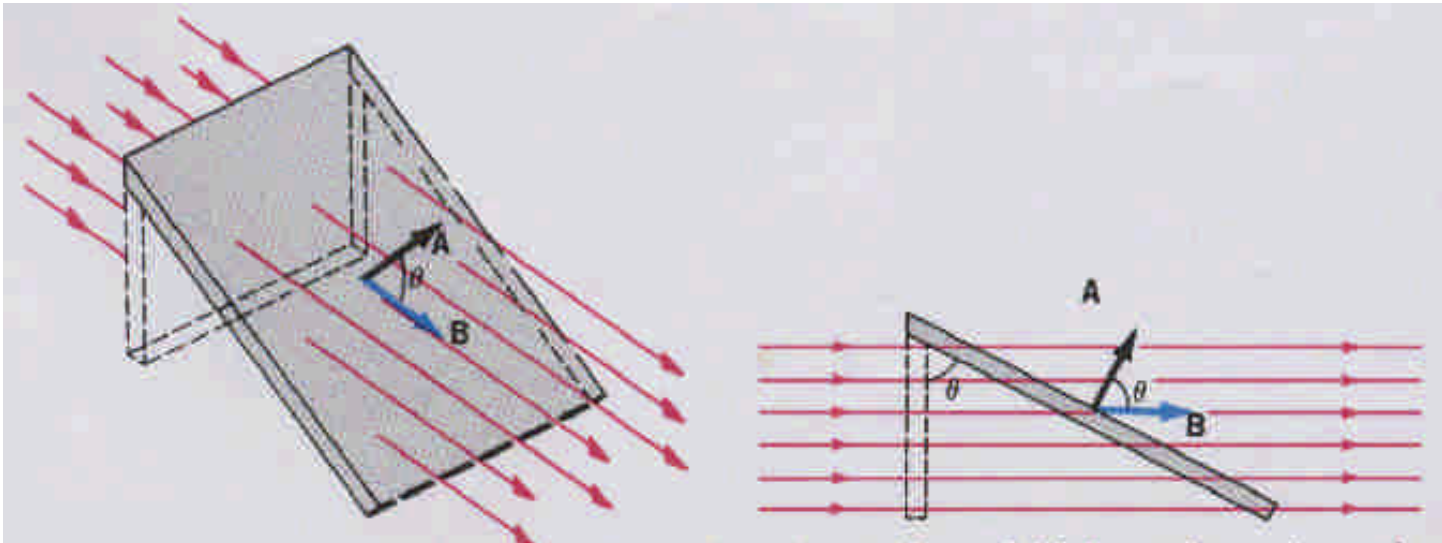


Fig.31.7

●Faraday's Law (法拉第定律) — 描述感應電動勢(induced emf)產生原因。

沿任意封閉路徑的感應電動勢(The induced emf)大小正比於穿越此路徑所圍面積之磁通量變化率。

$$\Rightarrow \xi \propto \frac{d\Phi}{dt} = \frac{dB}{dt} A \cos \theta + B \frac{dA}{dt} \cos \theta - BA \sin \theta \frac{d\theta}{dt}$$

(包括: B, A, θ 的變化率, 符合前述實驗)

●Lenz's Law (楞次定律) — 判斷感應電流或感應電動勢方向

感應電動勢的產生係反對磁通量變化, 分析 $\begin{cases} B_{ext} : \text{外部磁場} \\ B_{ind} : \text{感應磁場} \end{cases}$

$\Rightarrow \begin{cases} \text{當磁鐵靠近線圈}(B_{ext} \text{ 增加}) \Rightarrow B_{ind} \text{ 成反向, 抵消 } B_{ext} \text{ 的增加。} \\ \text{當磁鐵離開線圈}(B_{ext} \text{ 減小}) \Rightarrow B_{ind} \text{ 成同向, 彌補 } B_{ext} \text{ 的減小。} \end{cases}$

$\Rightarrow \begin{cases} B_{ind} \text{ 反向可推知感應電流 } I \text{ 為反時針方向。} \\ B_{ind} \text{ 同向可推知感應電流 } I \text{ 為順時針方向。} \end{cases}$

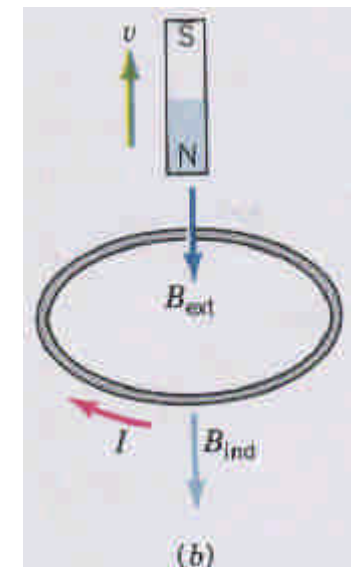
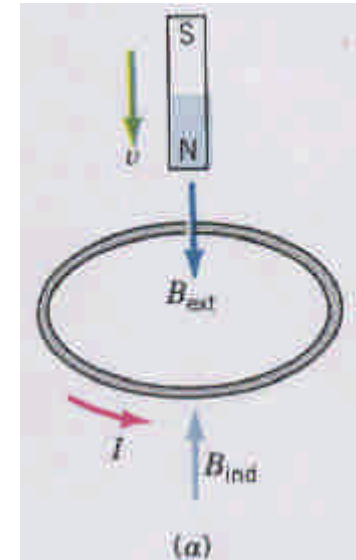


Fig.31.9

➤楞次定律是能量守恆的結果(Helmholtz)

—若 B_{ind} 係用來增強 B_{ext} ，則此增強的磁場會增大感應電流 I ，而增大的感應電流 I 將導致更大的磁場，又引發更大的感應電流 I ，如此一直下去是不可能的。

➤感應電動勢方向恆與磁通量變化相反。

感應電動勢方向的定義—由右手定則(right-hand rule)判定產生如Fig.31.10的磁場之迴路電流方向為正。

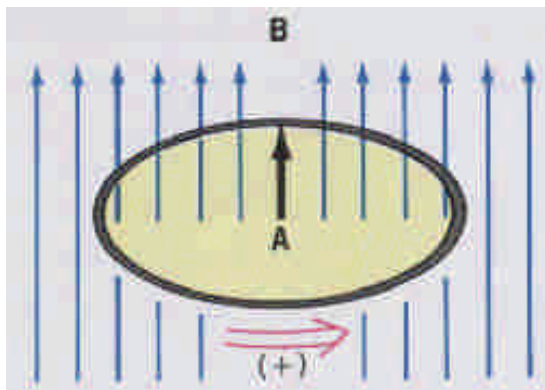


Fig.31.10

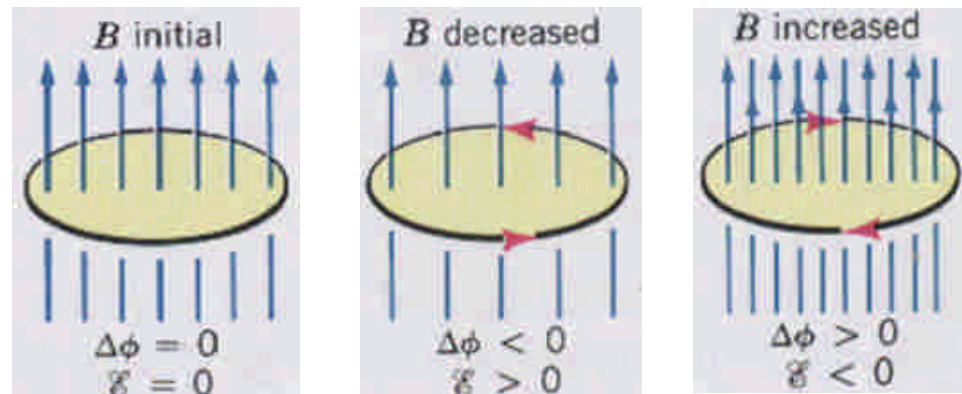


Fig.31.11

➤ Faraday's Law (+Lenz's Law) $\Rightarrow \xi = -\frac{d\Phi}{dt}$ (modern statement)

若考慮N匝 $\Rightarrow \xi = -N\frac{d\Phi}{dt}$ (such as solenoid or toroid)

Example 31.3 Find (a) the current in the resistor; (b) the power dissipated in the resistor; (c) the mechanical power needed to pull the rod.

$$\because \Phi = BA = B\ell x$$

$$\therefore |\xi| = \frac{d\Phi}{dt} = \frac{d}{dt}(B\ell x) = B\ell \frac{dx}{dt} = B\ell v$$

$$I = \frac{|\xi|}{R} = \frac{B\ell v}{R} \quad \text{— Ans (a)}$$

$$P_{elec} = I^2 R = \frac{(B\ell v)^2}{R^2} \cdot R = \frac{(B\ell v)^2}{R} \quad \text{— Ans (b)}$$

$$Rod \Rightarrow \begin{cases} \text{磁力向左} \Rightarrow \vec{F}_{mag} = I\vec{\ell} \times \vec{B} \Rightarrow F_{mag} = I\ell B \\ \text{外力向右} \xrightarrow{\text{因rod等速移動}} |\vec{F}_{ext}| = |\vec{F}_{mag}| = I\ell B \end{cases}$$

$$P_{mech} = \vec{F}_{ext} \cdot \vec{v} = I\ell Bv = \left(\frac{B\ell v}{R}\right)\ell Bv = \frac{(B\ell v)^2}{R} \quad \text{— Ans (c)}$$

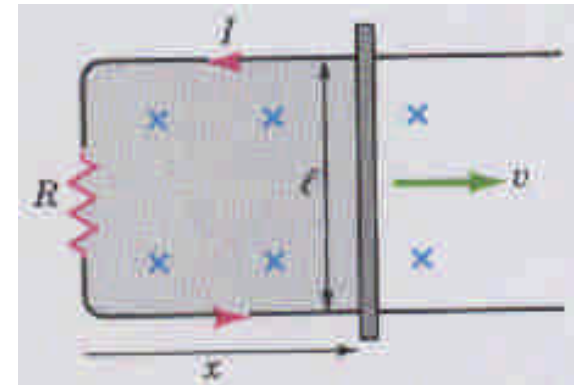


Fig.31.13

●Generators(發電機)

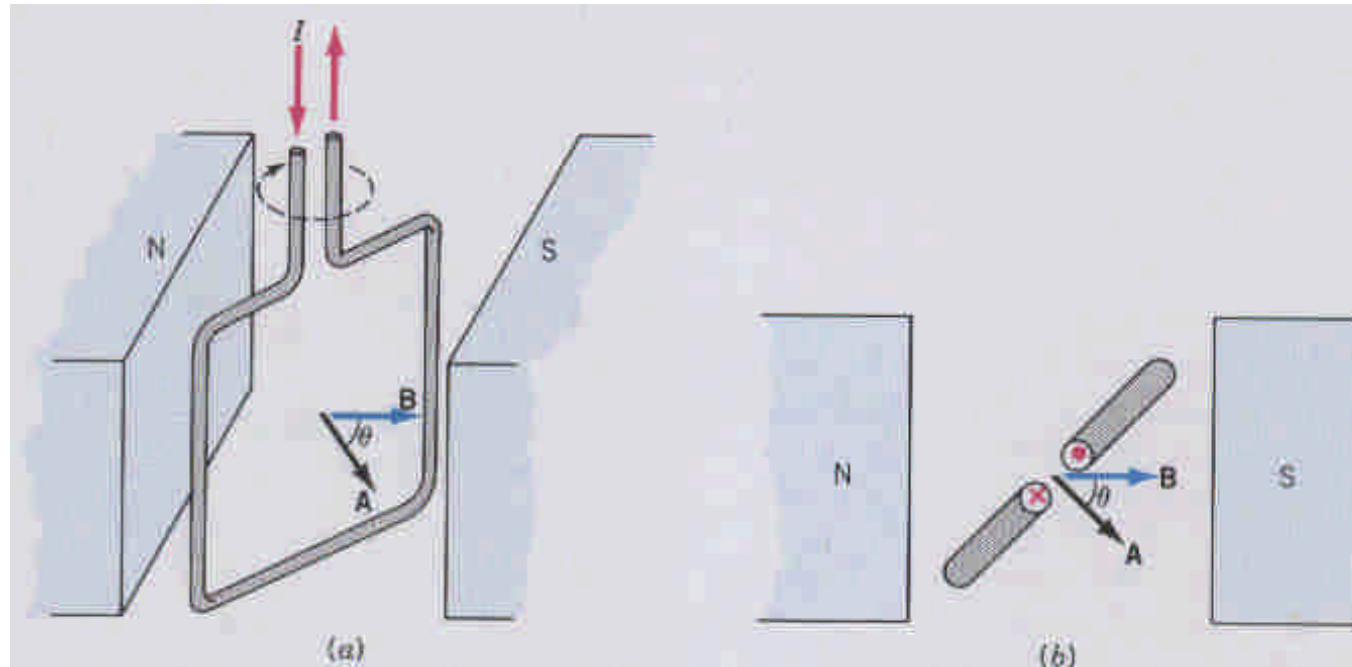
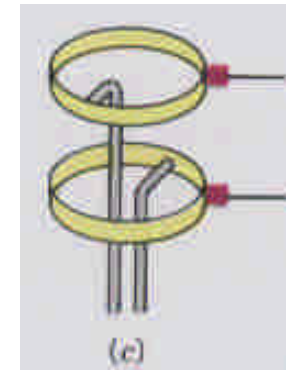


Fig.31.16



$$\text{磁通量} \Rightarrow \Phi = BA \cos(\theta) = BA \cos(\omega t)$$

$$\text{感應電動勢} \Rightarrow \xi = -N \frac{d\Phi}{dt} = NAB\omega \sin(\omega t)$$

$$\Rightarrow \xi = \xi_0 \sin(\omega t) \quad (\text{where } \xi_0 = NAB\omega)$$

—產生極性相反的交流電(alternating current)

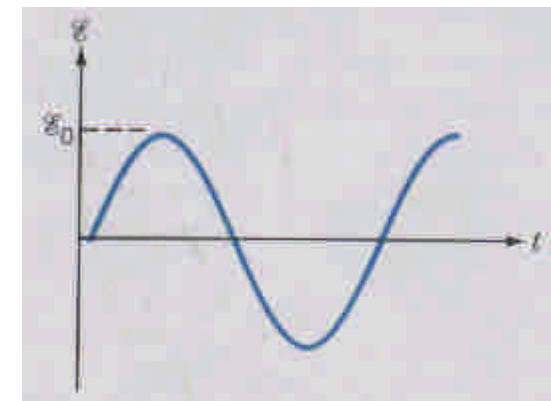


Fig.31.17

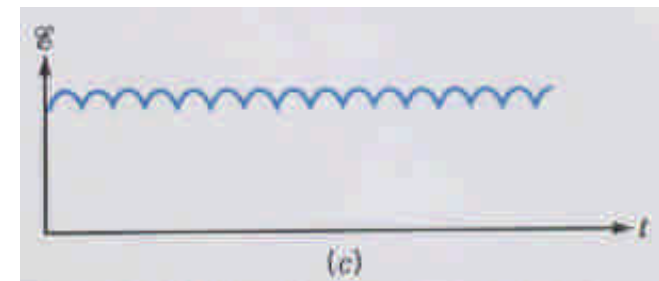
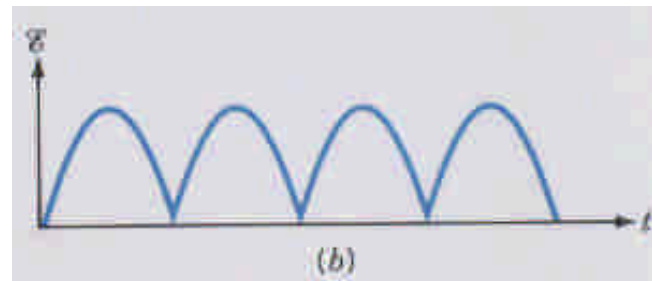
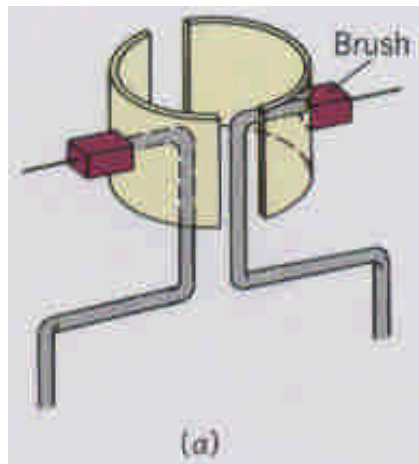
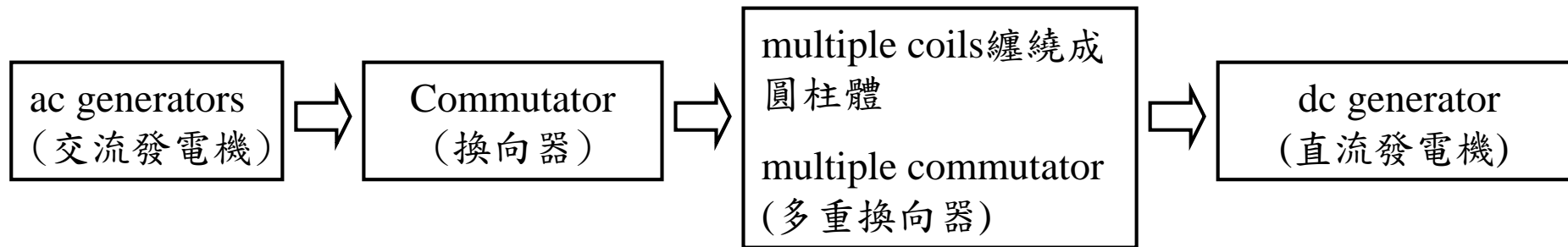


Fig.31.18

- The back emf of motors (電動機的反電動勢)

電動機原理—利用載流線圈在磁場中產生力矩來運轉。

反電動勢—線圈在磁場中運轉也會產生感應電動勢，但其方向與外部電動勢相反，即所謂的反電動勢(the back emf)，其大小與電動機運轉角速度(ω)成正比。

➤反電動勢(back emf)對電動機運作的影響

啟動瞬間電流相當大—電動機啟動瞬間，線圈靜止，無反電動勢產生，而線圈內阻又小，故啟動電流(startup current)相當大。

線圈轉動，電流減小—當線圈轉動將引發感應電動勢(即反電動勢)，可抵消部份之外部原有電動勢，導致淨電動勢(net emf)減小，故線圈通過的電流將減小。

No load (無負載)—電動機轉速會隨輸入能量(由外部電動勢產生)而增大，但反電動勢亦將隨轉速增大，造成淨電動勢(net emf)仍相當小，故線圈通過的電流不會大幅增加，因而線圈不致燒毀。

Load (接負載)—電動機轉速會減小，若負載太大促使轉速太小，感應的反電動勢就會相當小，則外部電動勢將形成足夠大的淨電動勢，造成線圈通過的電流大幅增加，最後導致線圈燒毀。

✦ The origins of the induced emf (感應電動勢的起因)

$$\xi = \frac{W_{ne}}{q} = \frac{1}{q} \oint \vec{F} \cdot d\vec{\ell} \xrightarrow{\vec{F}=q(\vec{E}+\vec{v} \times \vec{B})} \xi = \oint (\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{\ell}$$

$$\Rightarrow \xi = \oint \vec{E} \cdot d\vec{\ell} + \oint (\vec{v} \times \vec{B}) \cdot d\vec{\ell}$$

$$\Rightarrow \begin{cases} \xi = \oint \vec{E} \cdot d\vec{\ell} \text{ (} E \text{ 為感應電場) — 若線圈沒有相對於磁場運動，則磁場需隨時間變化} \\ \text{(類似電位差與電場關係式)} \\ \xi = \oint (\vec{v} \times \vec{B}) \cdot d\vec{\ell} \text{ (動生電動勢) — 若磁場不隨時間改變，則線圈需相對於磁場運動} \end{cases}$$

- Induced electric field (感應電場) — 線圈未運動、 $B \neq \text{const}$ ($v=0$)

$$\xi = \oint \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi}{dt} = -A \frac{dB}{dt}$$

$$\left(\frac{d\Phi}{dt} = \frac{d}{dt}(BA) = A \frac{dB}{dt} + B \frac{dA}{dt} \right)^0$$

因線圈截面未變

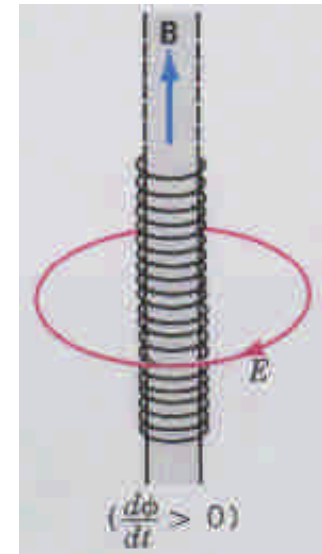


Fig.31.19

➤ 感應電場
與靜電場
的差異

感應電場的電力線(場線)是封閉的，而靜電場則有可能開放，如：靜電場起始或終止於點電荷。

感應電場屬於非保守場(nonconservative field)，沿封閉路徑的積分不等於零，而靜電場則為零，因靜電場為保守場。

Example 31.6 Find the induced electric field (a) inside (b) outside the solenoid.

$$\text{When } r < R \Rightarrow \oint \vec{E} \cdot d\vec{\ell} = E \oint d\ell = E(2\pi r)$$

$$= -A \frac{dB}{dt} = -(\pi r^2) \frac{dB}{dt}$$

$$\Rightarrow E = -\frac{r}{2} \frac{dB}{dt}$$

$$\text{When } r > R \Rightarrow \oint \vec{E} \cdot d\vec{\ell} = E(2\pi r) = -(\pi R^2) \frac{dB}{dt}$$

$$\Rightarrow E = -\frac{R^2}{2r} \frac{dB}{dt}$$

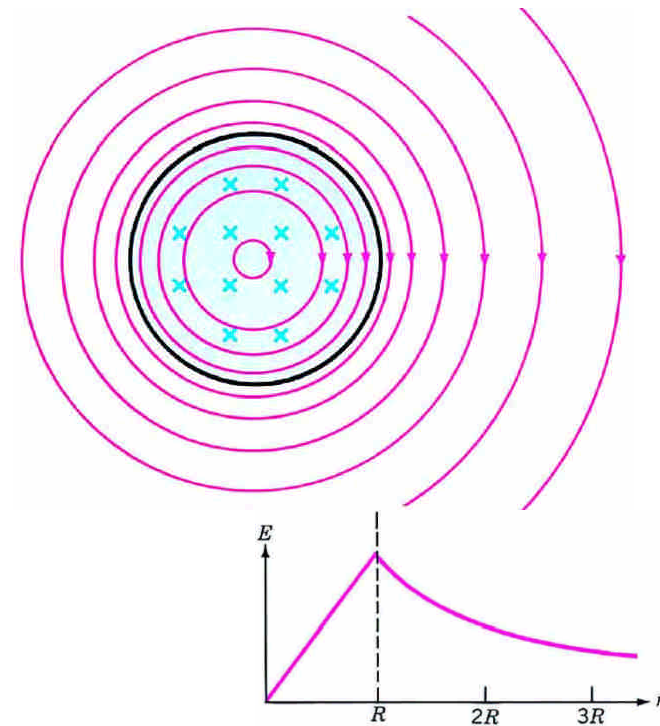


Fig.31.20

Note: 螺線管外的感應電場係由電荷產生，因時變(time-depend)的磁場與感應電場會導致電荷加速。

- Motion emf (動生電動勢) — 線圈相對於磁場運動、 $B = \text{const.}$

$$\xi = \oint (\vec{v} \times \vec{B}) \cdot d\vec{\ell} = -\frac{d\Phi}{dt}$$

➤ 導體棒移動產生電動勢(emf)

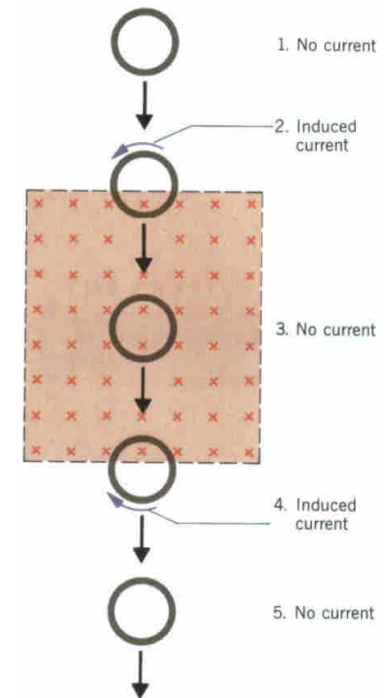
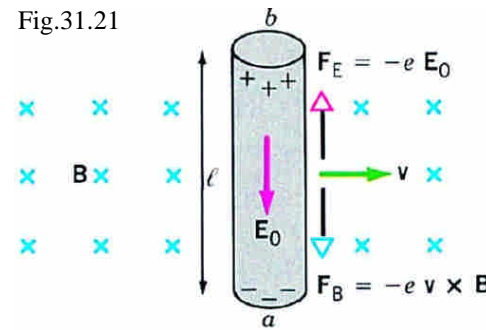
$$\vec{F}_B = -e\vec{v} \times \vec{B} \xrightarrow{\text{驅使電子向下}} \vec{F}_E = -eE_0$$

$$\xrightarrow{\vec{F}_B \text{ 與 } \vec{F}_E \text{ 平衡 (電子不再移動)} \Rightarrow F_E = F_B} E_0 = vB$$

$$\xrightarrow{\text{由兩端聚集正負電荷所形成的靜電場 } E_0 \text{ 產生端電位差}} V_B - V_A = E_0 \ell = B\ell v$$

$$\xrightarrow{\text{端電位差=動生電動勢}} \xi = B\ell v$$

Fig.31.21



➤ 磁力不會作功：

假設電子 $\left\{ \begin{array}{l} \text{隨導體棒水平運動速率為 } v。 \\ \text{沿導體棒垂直漂移速率為 } v_d。 \end{array} \right.$

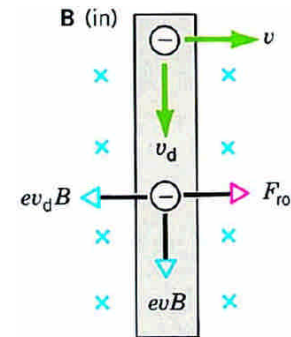
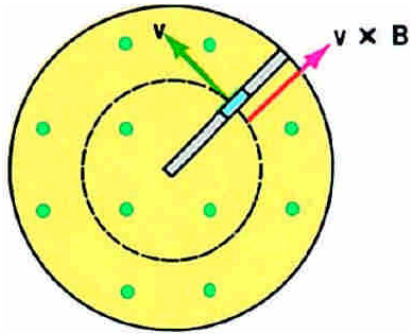


Fig.31.24

$$\boxed{\text{磁力產生的功率 } P = \vec{F} \cdot \vec{v}} \Rightarrow \left\{ \begin{array}{l} \text{垂直方向： } P_{\text{垂直}} = evBv_d (\because F_B = evB, \vec{F}_B \text{ 與 } \vec{v}_d \text{ 方向相同}) \\ \text{水平方向： } P_{\text{水平}} = -ev_d Bv (\because F_B = ev_d B, \vec{F}_B \text{ 與 } \vec{v} \text{ 方向相反}) \end{array} \right.$$

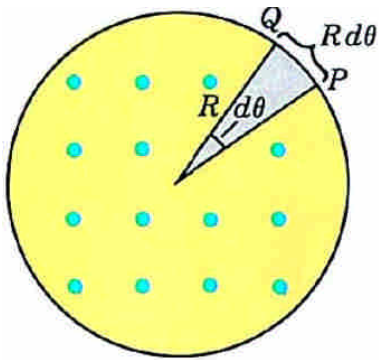
$$\boxed{\text{磁力的淨功率}} \Rightarrow P_{\text{net}} = P_{\text{垂直}} + P_{\text{水平}} = 0 \quad (\text{如此可證實磁力不作功})$$

Example 31.7 Find the emf of a homopolar generator(單極發電機).



$$\xi = \int (\vec{v} \times \vec{B}) \cdot d\vec{\ell} = \int v B dr$$

$$= \int r \omega B dr = \omega B \int_0^R r dr = \frac{1}{2} \omega B R^2$$



$$|\xi| = \frac{d\Phi}{dt} = \frac{B dA}{dt} = \frac{B \left[\frac{1}{2} R (R d\theta) \right]}{dt}$$

$$= \frac{1}{2} B R^2 \frac{d\theta}{dt} = \frac{1}{2} B R^2 \omega = \frac{1}{2} \omega B R^2$$

Fig.31.23

✦ 渦電流 (Eddy current)

Case(a) 磁棒垂直導體平板移動

— 磁棒靠近導體平板，因導體平板上任意迴路的磁通量發生改變，故感應出逆時針的渦電流；反之，若遠離則感應順時針渦電流。

Case(b) 磁棒平行導體平板移動

- 遠離區域的感應渦電流為順時針
(磁通量減小，產生吸力)
- 靠近區域的感應渦電流為逆時針
(磁通量增加，產生斥力)

Case(c) 導體平板在均勻磁場中移動

— 導體平板遠離磁場運動會產生順時針的感應電流，導致平板受到向左的吸力(可由 $\vec{F} = I\vec{\ell} \times \vec{B}$ 判定)，此力與其運動方向相反。

➤ 感應渦電流磁力的應用 — 電子天平或檢流計之線圈振盪減緩、火車煞車系統、汽車速率錶。

➤ 渦電流在導體內運動時，會產生熱能，如：半導體的熔冶及精化、電磁爐。

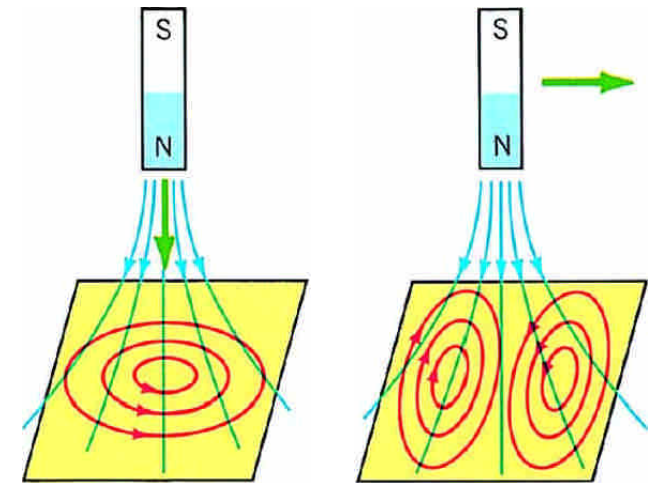


Fig.31.25

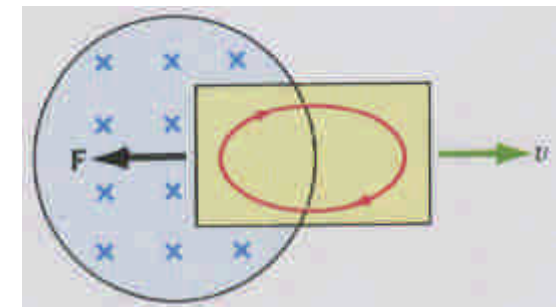


Fig.31.26

- 磁鐵懸浮實驗—繞鉛直軸快速旋轉的導體圓盤邊上的磁鐵，渦電流的磁力會導致磁鐵沿盤緣運動方向移動。
- 跳彈實驗—將螺線管纏繞在鐵棒，再將銅環套在鐵棒上，當AC電流通上螺線管，銅環會因渦電流的斥力而被推開垂直向上飛去。
- 感應渦電流磁力的應用—火車的磁浮與推進上。
(斥力)

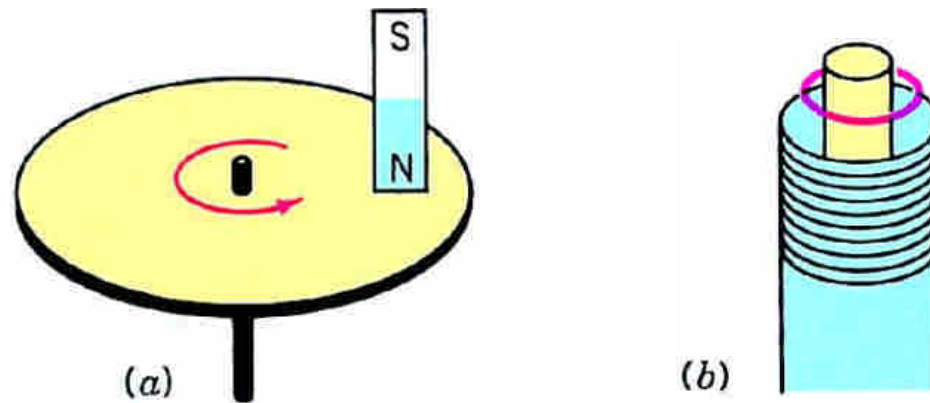


Fig.31.27

✦ 電感(Inductance) — 線圈因電流變化而產生感應電動勢

- { 自感(Self-Induction)⇒線圈因本身電流變化造成磁通量改變而產生感應電動勢。
 { 互感(Mutual-Induction)⇒線圈的磁通量改變係由其他線圈造成。

$$\xi = -\frac{d(N\Phi)}{dt}$$

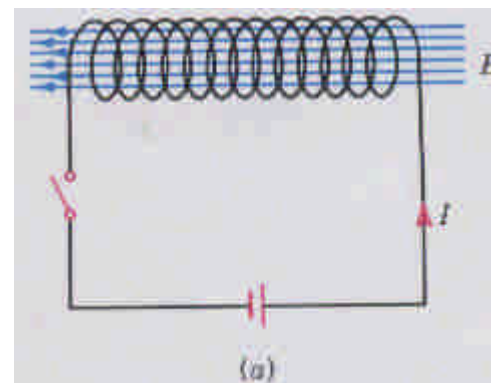
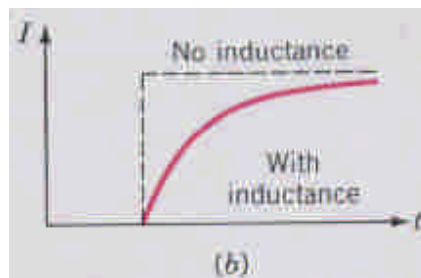


Fig.32.2

其中 $N\Phi$ 為磁通量或磁交鏈數(The flux linkage)

Example：如圖32.3

$$N_1\Phi_1 = N_1(\Phi_{11} + \Phi_{12})$$

$$\begin{aligned}
 \Rightarrow \xi_1 &= -N_1 \frac{d}{dt} (\Phi_{11} + \Phi_{12}) \\
 &= -N_1 \frac{d}{dt} \Phi_{11} - N_1 \frac{d}{dt} \Phi_{12} \\
 &\quad \text{(自感)} \quad \quad \text{(互感)}
 \end{aligned}$$

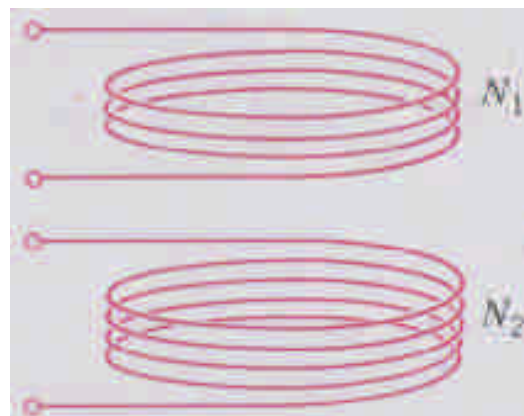


Fig.32.3

• 自感 $\Rightarrow N_1 \Phi_{11} = L_1 I_1$ (L_1 為比例常數，稱為線圈1的自感值)

$$\Rightarrow \xi_{11} = -N_1 \frac{d\Phi_{11}}{dt} = -L_1 \frac{dI_1}{dt} \quad (\xi_{11} \text{極性僅與 } \frac{dI_1}{dt} \text{ 有關})$$

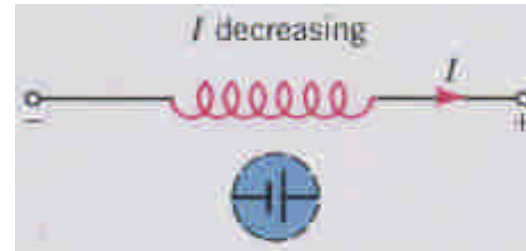


Fig.32.4

• 互感 $\Rightarrow N_1 \Phi_{12} = M_{12} I_2$ or $N_2 \Phi_{21} = M_{21} I_1$ ($M_{12}=M_{21}=M$ ， M 稱為互感值)

$$\Rightarrow \xi_{12} = -N_1 \frac{d\Phi_{12}}{dt} = -M \frac{dI_2}{dt}$$

In sum,

$$\Rightarrow \xi_1 = -N_1 \frac{d}{dt} (\Phi_{11} + \Phi_{12}) = \xi_{11} + \xi_{12}$$

Example 32.1 A long solenoid of length ℓ and cross-sectional area A has N turns. Find its self-inductance.

$$\Phi = BA = \mu_0 n I A \Rightarrow L = \frac{N \Phi}{I} = N \mu_0 n A = n \ell \mu_0 n A = \mu_0 n^2 A \ell$$

$(\because n = N / \ell)$

Example 32.3 A small coil placed within a solenoid. What is their mutual inductance?

已知： A small coil $\Rightarrow A_1, N_1$
A long solenoid $\Rightarrow A_2, n_2$

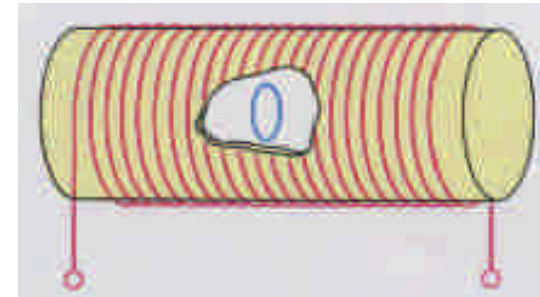


Fig.32.6

$$\Phi_{12} = B_2 A_1 = (\mu_0 n_2 I_2) A_1 \Rightarrow M = \frac{N_1 \Phi_{12}}{I_2} = \mu_0 n_2 N_1 A_1$$

✦ LR 電路 (LR circuits)

- 充電(Rise) $\Rightarrow \left[\frac{dI}{dt} > 0 \Rightarrow \xi_L = -L \frac{dI}{dt} = V_a - V_b > 0 \right]$

From Kirchhoff's loop rule : $\xi - IR - L \frac{dI}{dt} = 0$

$$\Rightarrow \frac{\xi}{R} - I - \frac{L}{R} \frac{dI}{dt} = 0 \xrightarrow{\text{Let } y = \frac{\xi}{R} - I, \frac{dy}{dt} = -\frac{dI}{dt}} y + \frac{L}{R} \frac{dy}{dt} = 0$$

$$\Rightarrow \frac{dy}{y} = -\frac{R}{L} dt \Rightarrow \ln y = -\frac{R}{L} t + \ln y_0 \Rightarrow y = y_0 e^{-Rt/L}$$

$$\Rightarrow \frac{\xi}{R} - I = y_0 e^{-Rt/L} \xrightarrow[\text{initial cond.}]{I=0 \text{ at } t=0} y_0 = \frac{\xi}{R}$$

$$\Rightarrow \frac{\xi}{R} - I = \frac{\xi}{R} e^{-Rt/L} \Rightarrow I = \frac{\xi}{R} (1 - e^{-Rt/L})$$

$$\xrightarrow{I_0 = \frac{\xi}{R}} I = I_0 (1 - e^{-Rt/L}) \xrightarrow{\tau = L/R} I = I_0 (1 - e^{-t/\tau})$$

When $t = \tau \Rightarrow I = I_0 (1 - e^{-1}) \approx 0.63 I_0$

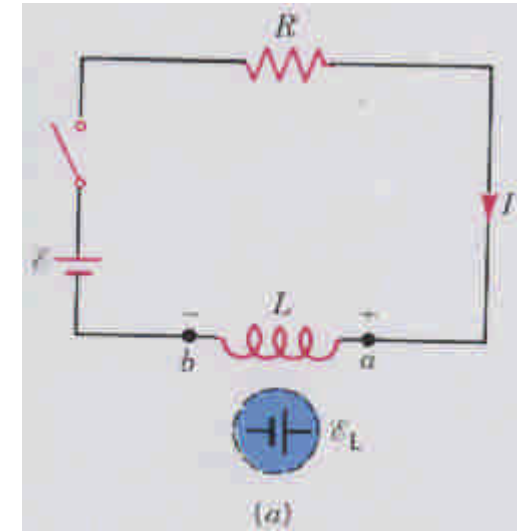
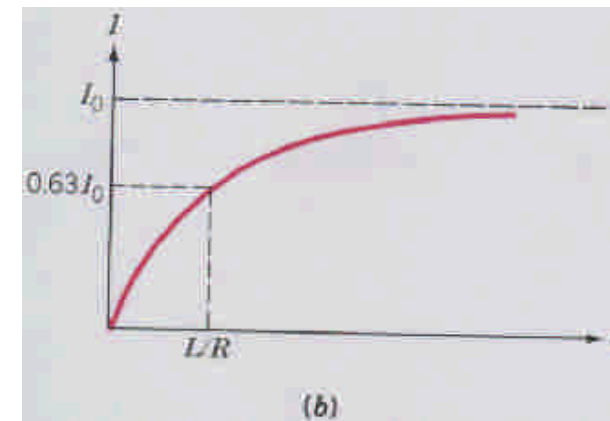


Fig.32.7



●放電(Decay) $\Rightarrow \left[\frac{dI}{dt} < 0 \Rightarrow \xi_L = -L \frac{dI}{dt} = V_a - V_b > 0 \right]$

From Kirchhoff's loop rule : $-IR - L \frac{dI}{dt} = 0$

$$\Rightarrow \frac{dI}{I} = -\frac{R}{L} dt \Rightarrow \ln I = -\frac{R}{L} t + \ln I_0$$

$$\xrightarrow[\text{initial cond.}]{I=I_0=\xi/R \text{ at } t=0} I = \frac{\xi}{R} e^{-Rt/L} \Rightarrow I = I_0 e^{-t/\tau}$$

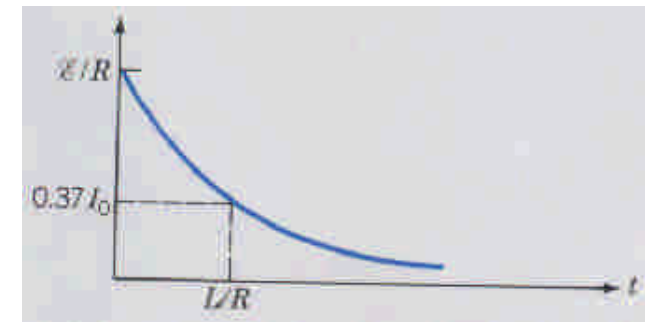
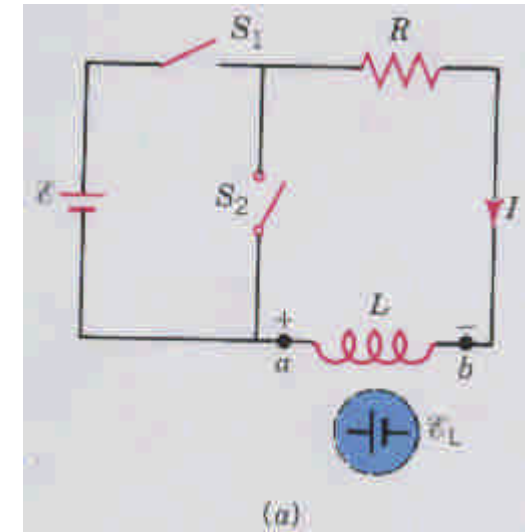


Fig.32.8

$$\text{Initial condition} \Rightarrow \begin{cases} \text{Rise} \Rightarrow I = 0 \text{ (斷路)} \\ \text{Decay} \Rightarrow I = I_0 \text{ (短路)} \end{cases}$$

$$\text{Steady state} \Rightarrow \begin{cases} \text{Rise} \Rightarrow I = I_0 \text{ (短路)} \\ \text{Decay} \Rightarrow I = 0 \text{ (斷路)} \end{cases}$$

✦ 儲存於電感的能量(Energy stored in an inductor)

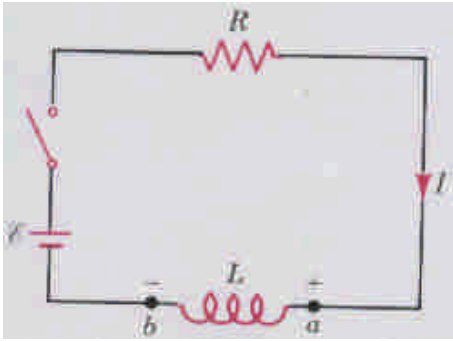


Fig.32.7

$$\xi - iR - L \frac{di}{dt} = 0 \Rightarrow \xi = iR + L \frac{di}{dt}$$

$$\Rightarrow i\xi = i^2 R + Li \frac{di}{dt}$$

$$\left\{ \begin{array}{l} i\xi \Rightarrow \text{the power supplied by battery} \\ i^2 R \Rightarrow \text{the power dissipated by resistor} \\ Li \frac{di}{dt} \Rightarrow \text{the power supplied by inductor} \end{array} \right.$$

$$\frac{dU_L}{dt} = Li \frac{di}{dt} \Rightarrow \text{The total energy} : U_L = L \int_0^I i di = \frac{1}{2} LI^2$$

$$\xrightarrow[\text{Solenoid}]{L = \mu_0 n^2 A \ell} U_L = \frac{1}{2} (\mu_0 n^2 A \ell) I^2 \xrightarrow[\text{Solenoid}]{B = \mu_0 n I} U_L = \frac{B^2}{2\mu_0} A \ell$$

$$\text{Energy density} : u_B = \frac{U_L}{A \ell} = \frac{B^2}{2\mu_0}$$

Example 32.6: The self-inductance of a toroid.

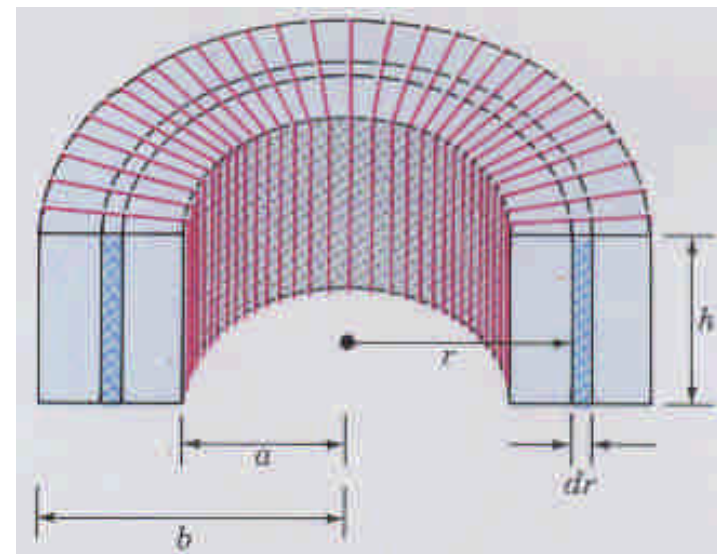
$$B = \frac{\mu_0 NI}{2\pi r}, \quad u_B = \frac{B^2}{2\mu_0}, \quad dV = h(2\pi r dr)$$

$$dU = u_B dV = \left(\frac{B^2}{2\mu_0}\right) h(2\pi r dr) = \frac{\mu_0 N^2 I^2 h}{4\pi} \frac{dr}{r}$$

$$U = \int dU = \frac{\mu_0 N^2 I^2 h}{4\pi} \int_a^b \frac{dr}{r} = \frac{\mu_0 N^2 I^2 h}{4\pi} \ln \frac{b}{a}$$

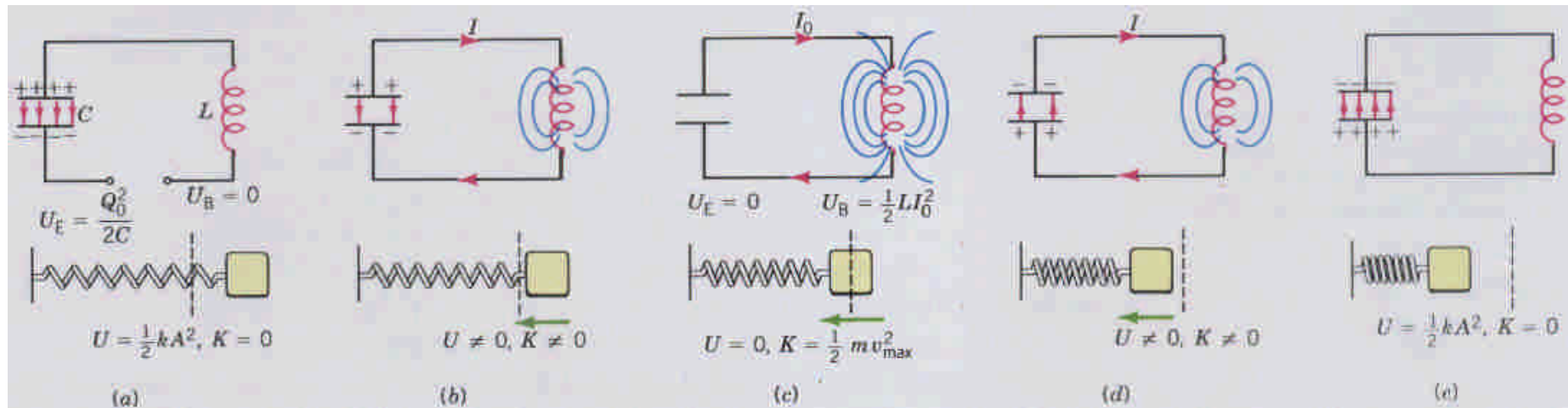
$$\text{From } U = \frac{1}{2} LI^2 \Rightarrow L = \frac{\mu_0 N^2 h}{2\pi} \ln \frac{b}{a}$$

Fig.32.9



✦ LC振盪(LC oscillations)

Fig.32.10



From Kirchhoff's loop rule : $\frac{Q}{C} - L \frac{dI}{dt} = 0 \xrightarrow{\because I = -\frac{dQ}{dt}} \frac{Q}{C} + L \frac{d^2 Q}{dt^2} = 0$

$$\Rightarrow \frac{d^2 Q}{dt^2} + \frac{1}{LC} Q = 0 \xrightarrow[\text{簡諧振盪}]{\frac{d^2 x}{dt^2} + \omega^2 x = 0} Q = Q_0 \sin(\omega_0 t + \phi)$$

where $\omega_0 = \frac{1}{\sqrt{LC}}$ (natural angular frequency)

$$\xrightarrow[\text{initial cond.}]{Q=Q_0 \text{ at } t=0} \phi = \pi / 2 \Rightarrow Q = Q_0 \cos(\omega_0 t)$$

$$\xrightarrow{I = \frac{dQ}{dt}} I = I_0 \sin(\omega_0 t)$$

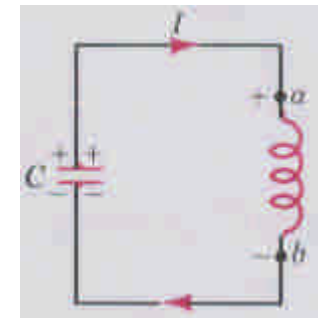


Fig.32.11

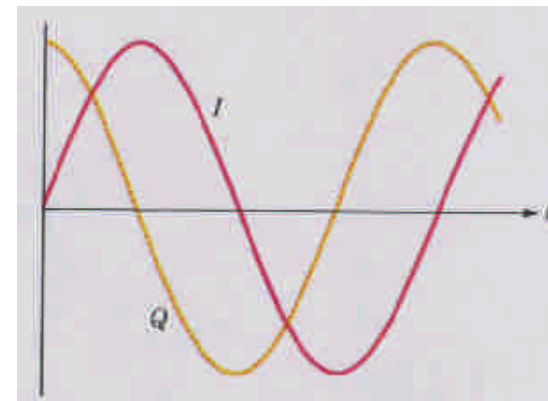


Fig.32.12

the total energy $\Rightarrow U = U_E + U_B = \frac{Q_0^2}{2C} \cos^2(\omega_0 t) + \frac{LI_0^2}{2} \sin^2(\omega_0 t)$

$\because I_0 = \omega_0 Q_0$ and $\omega_0 = \frac{1}{\sqrt{LC}} \quad \therefore U = \frac{Q_0^2}{2C} = \frac{LI_0^2}{2} = \text{constant}$

TABLE 32.1 ANALOGIES BETWEEN MECHANICAL AND ELECTRICAL QUANTITIES

Mechanical:	x	v	m	$\frac{1}{2}mv^2$	k	$\frac{1}{2}kx^2$	F	$P = Fv$
Electrical:	Q	I	L	$\frac{1}{2}LI^2$	$\frac{1}{C}$	$\frac{1}{2}\frac{Q^2}{C}$	V	$P = VI$

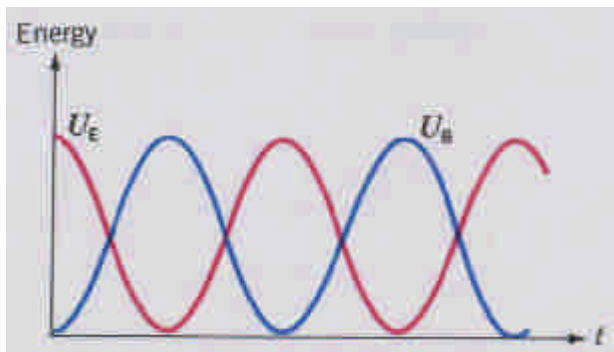


Fig.32.13

純LC振盪是不合理的，理由如下：

- 1.任何電感器皆有電阻。
- 2.能量會以電磁波方式輻散，不能維持定值。

• 阻尼LC振盪(Damped LC oscillations)

From Kirchhoff's loop rule : $\frac{Q}{C} - IR - L \frac{dI}{dt} = 0 \xrightarrow{I = -\frac{dQ}{dt}}$

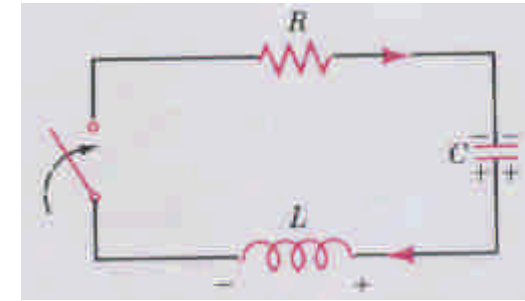


Fig.32.14

$$L \frac{d^2 Q}{dt^2} + R \frac{dQ}{dt} + \frac{Q}{C} = 0 \xrightarrow[\text{damped harmonic motion}]{m \frac{d^2 x}{dt^2} + \gamma \frac{dx}{dt} + kx = 0} Q = Q_0 e^{-Rt/2L} \cos(\omega' t + \delta)$$

where $\omega' = \sqrt{\omega_0^2 - \left(\frac{R}{2L}\right)^2}$ $\begin{cases} \omega_0 > R/2L \Rightarrow R < 2\omega_0 L \text{ (under-damped)} \\ \omega_0 = R/2L \Rightarrow R = 2\omega_0 L \text{ (critically damped)} \\ \omega_0 < R/2L \Rightarrow R > 2\omega_0 L \text{ (over-damped)} \end{cases}$

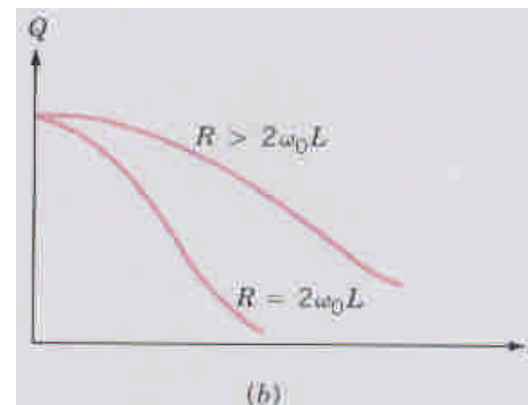
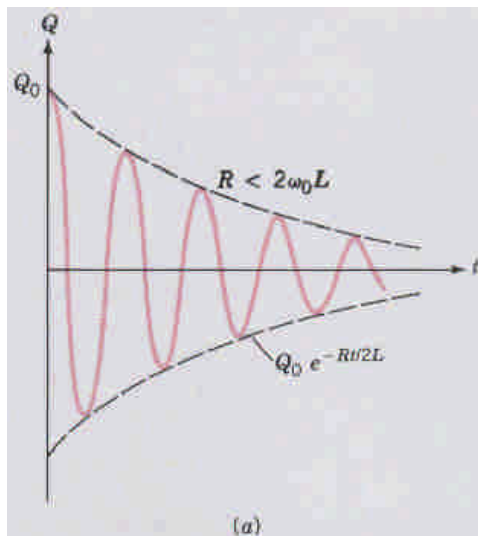


Fig.32.15

✦ 物質的磁性質 (Magnetic properties of matter)

• 磁性物質與磁棒的作用

鐵磁性(ferromagnetic)－被吸向磁場最強區域。

(Fe, Ni, Co, Gd, Dy, CrO₂, EuO, Fe₂O₃)

順磁性(paramagnetic)－被吸向磁場最強區域，但吸力較弱。

(Al, Cr, K, Mg, Mn, Na)

反磁性(diamagnetic)－傾向移至磁場較弱的區域。

(抗磁性)(Cu, Bi, C, Ag, Au, Pb, Zn)

物質本身所生磁場 $B_M = \chi_m B_0$ ， χ_m 稱為磁化率

物質內總磁場 $B = B_0 + B_M = (1 + \chi_m) B_0 = \kappa_m B_0$

$$\begin{cases} \text{鐵磁性} \Rightarrow \chi_m = 10^3 \sim 10^5 \\ \text{順磁性} \Rightarrow \chi_m = 10^{-5} \\ \text{反磁性} \Rightarrow \chi_m = -10^{-5} \end{cases}$$

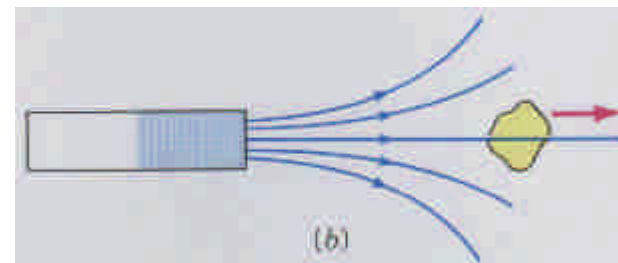
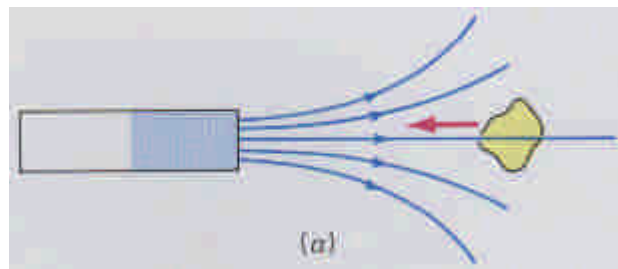


Fig.32.16

●物質磁性產生的原因

— 主要與電子運動有關，因其可建立電流，形成磁偶極矩，進而產生磁場。

$$\mu = \frac{eL}{2m} \xrightarrow{L=n\hbar} \text{Bohr magneton } \mu_B = \frac{e\hbar}{2m} \Rightarrow \begin{cases} \text{電子繞原子核(質子)運動。} \\ \text{電子自旋運動。} \end{cases}$$

(波耳磁元)

反磁性物質—無永久磁偶極矩，淨磁場比外加磁場小(可由楞次定律解釋)，超導體是理想的抗磁性物質($\chi = -1$)。

順磁性物質—具永久磁偶極矩，但彼此交互作用很弱且方向紊亂，常因熱擾動而無法完全與磁場同向排列，故僅有部份磁偶極矩排列可增強外加磁場，其中初始線性部份可由居禮定律(Curie's Law)描述，即 $M = C(B/T)$ 。當磁場增大或溫度降低，磁化強度會達到飽和。

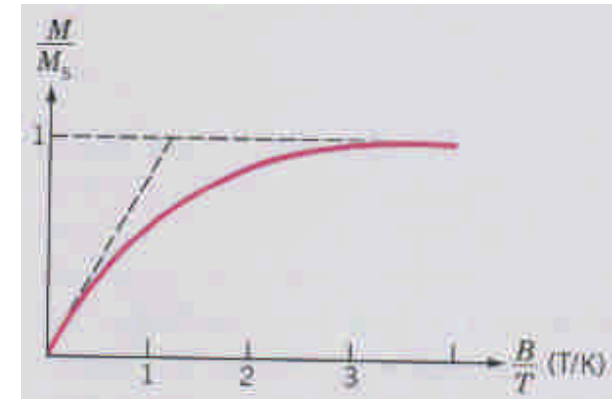


Fig.32.17

鐵磁性物質—每個原子皆因未成對電子自旋而造成磁矩，相鄰原子的磁矩會傾向平行排列，但只有在1 mm大小的磁域 (magnetic domain)才完全平行。當外加磁場作用時，磁矩與外加磁場平行的磁域會增大且其他磁域也會轉向與外加磁場同向。當重擊，磁域間會失去順向排列；當溫度增高，飽和磁化強度將降低，若高於居禮溫度(Curie temperature, T_c)，則鐵磁性物質將變為順磁性物質。

Fig.32.18

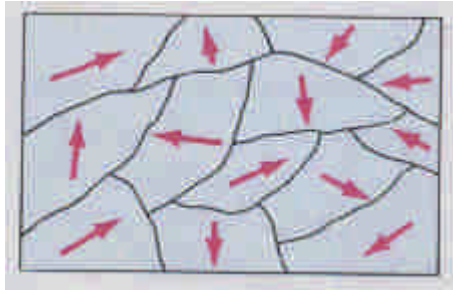


Fig.32.21

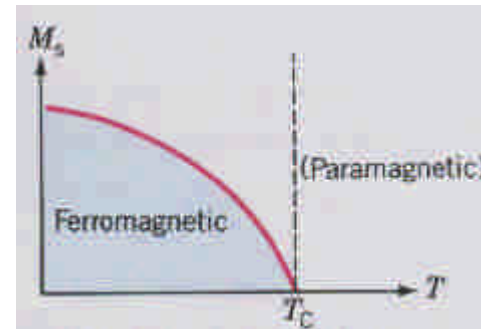
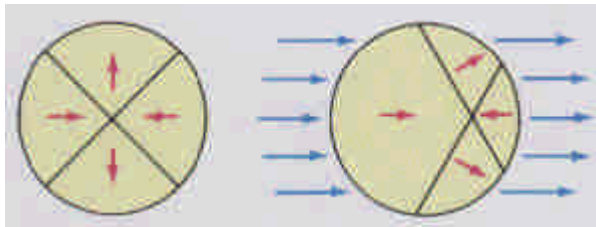


Fig.32.22

Fig.32.23

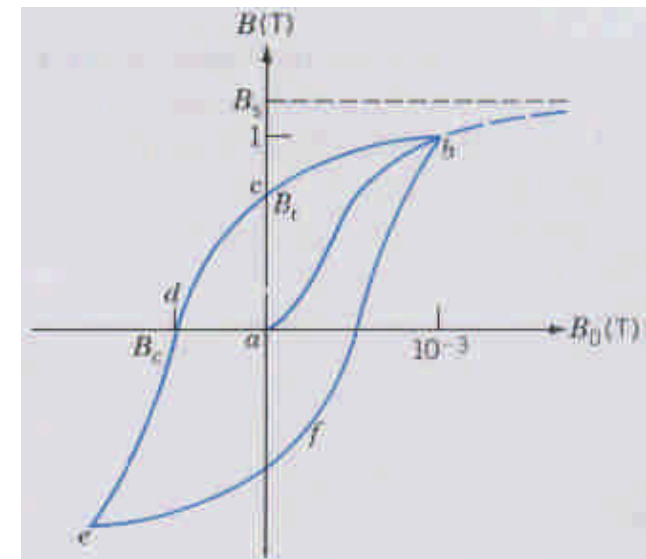
● 磁滯現象(magnetic hysteresis)

一大部份磁域轉向平行外加磁場 B_0 後，便不能回至原來方向。

➤ 矯頑力(coercive force)

— 摧毀磁化的困難度。(即磁場 B_c)

矯頑力大稱硬磁物質，矯頑力小稱軟磁物質。



硬磁物質可做永久磁鐵，如揚聲器與動線圈表頭。

軟磁物質磁滯迴路面積小，熱消耗小，適合應用在變壓器、電磁鐵、磁帶及電腦磁片。

- 去磁(demagnetize)一經一連串外加磁場減小的磁滯曲線，如圖所示，振盪磁場可由交流電路通過線圈產生，然後，再將線圈遠離磁化物質。

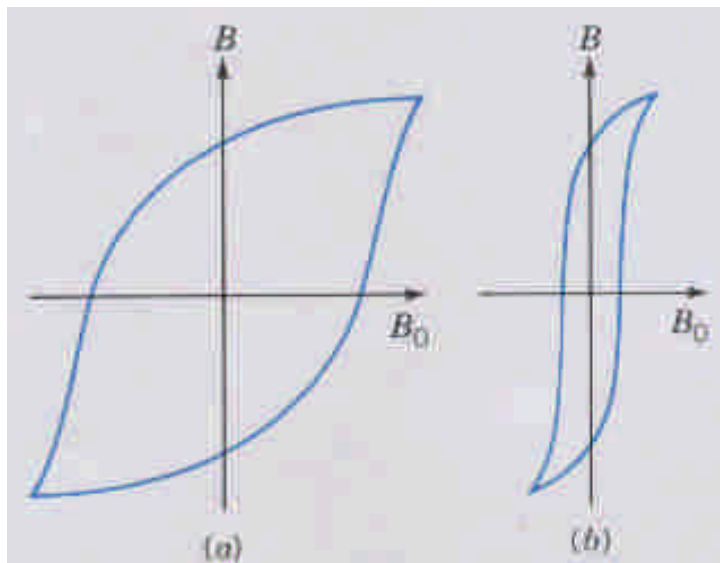


Fig.32.24

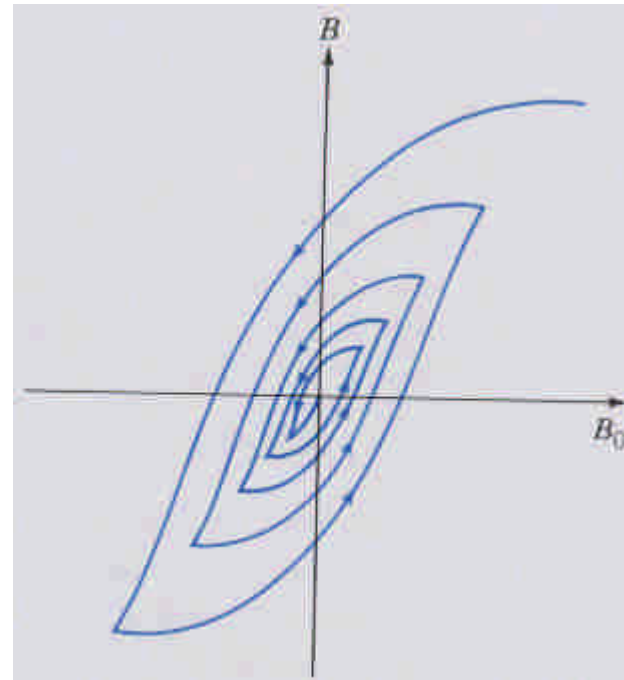


Fig.32.25