Electrodynamics-II

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ˉ.2 Electromagnetic Induction

7.2.1 Faraday's Law

In 1831 Michael Faraday reported on a series of experiments, including three that (with some violence to history) can be characterized as follows:

Experiment 1. He pulled a loop of wire to the right through a magnetic field (Fig. 7.20a). A current flowed in the loop.

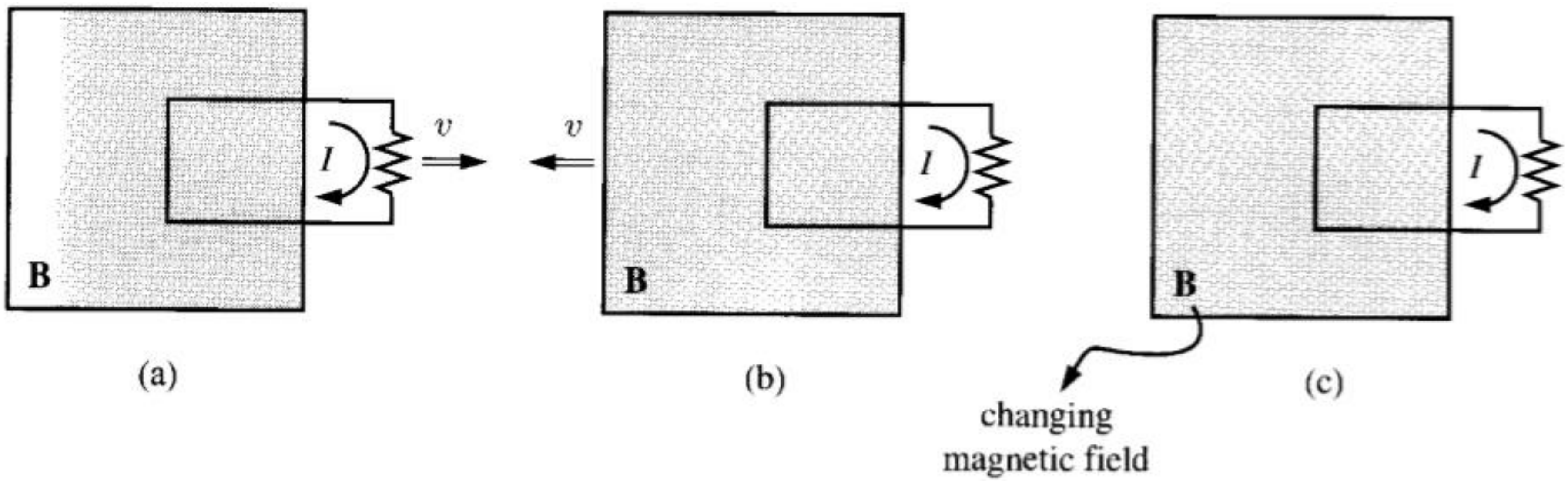

Figure 7.20

Experiment 2. He moved the *magnet* to the *left*, holding the loop still (Fig. 7.20b). Again, a current flowed in the loop.

Experiment 3. With both the loop and the magnet at rest (Fig. 7.20c), he changed the *strength* of the field (he used an electromagnet, and varied the current in the coil). Once again, current flowed in the loop.

The first experiment, of course, is an example of motional emf, conveniently expressed by the flux rule:

$$\mathcal{E} = -\frac{d\Phi}{dt}.$$

Same EMF arises in loop 2

The thing that really matters is the relative motion between magnet and the loop

- If loop moves, it is the magnetic force that produces the emf in the loop.
- But if the loop is stationary, the force cannot be magnetic one.

What sort of field exerts a force on charges at rest?

Ans: Well it is the electric field that is produced by the changing magnetic field.

- So we can say

A changing magnetic field induces an electric field.

It is this "induced" electric field that accounts for the emf in Experiment 2.[6] Indeed, if (as Faraday found empirically) the emf is again equal to the rate of change of the flux,

$$\mathcal{E} = \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi}{dt}, \tag{7.14}$$

then **E** is related to the change in **B** by the equation

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{a}. \tag{7.15}$$

This is **Faraday's law**, in integral form. We can convert it to differential form by applying Stokes' theorem:

$$\boxed{\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}.} \tag{7.16}$$

Note that Faraday's law reduces to the old rule $\oint \mathbf{E} \cdot d\mathbf{l} = 0$ (or, in differential form, $\nabla \times \mathbf{E} = 0$) in the static case (constant **B**) as, of course, it should.

In Experiment 3 the magnetic field changes for entirely different reasons, but according to Faraday's law an electric field will again be induced, giving rise to an emf $-d\Phi/dt$. Indeed, one can subsume all three cases (and for that matter any combination of them) into a kind of **universal flux rule**:

> Whenever (and for whatever reason) the magnetic flux through a loop changes, an emf
>
> $$\mathcal{E} = -\frac{d\Phi}{dt} \tag{7.17}$$
>
> will appear in the loop.

Two Different Phenomenon in the Faraday's Law

Example 7.5

A long cylindrical magnet of length L and radius a carries a uniform magnetization $\mathbf{M}$ parallel to its axis. It passes at constant velocity v through a circular wire ring of slightly larger diameter (Fig. 7.21). Graph the emf induced in the ring, as a function of time.

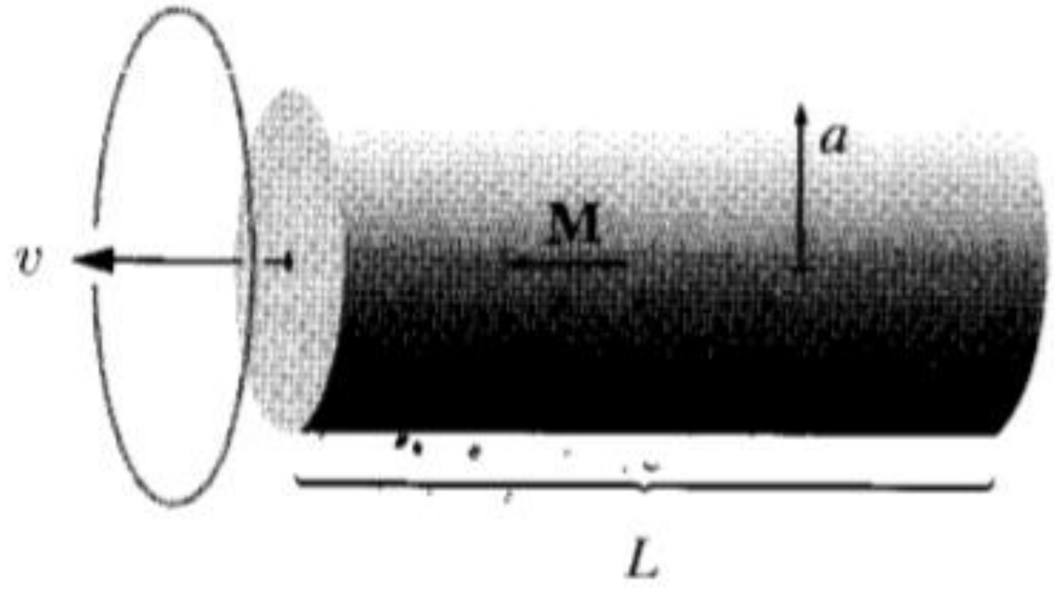

Figure 7.21

Solution

Surface current will be same as in the case of solenoid

$$\vec{K} = \vec{M} \times \hat{n} = M\hat{\emptyset}$$

Field inside the solenoid is

$$\vec{B} = \mu_0 n I \hat{z} = \mu_0 \left(\frac{NI}{L}\right)\hat{z} = \mu_0 \vec{M}$$

$\frac{NI}{L}$ **represents the total surface current per unit length is** K

$$\vec{B} = \mu_0\, K\hat{z} = \mu_0 \vec{M} \qquad because\ |\vec{K}| = M$$

The flux through the ring is zero when the magnet is far away; it builds up to a maximum of $\mu_0 M\pi a^2$ as the leading end passes through; and it drops back to zero as the trailing end emerges (Fig. 7.22a). The emf is (minus) the derivative of Φ with respect to time, so it consists of two spikes, as shown in Fig. 7.22b.

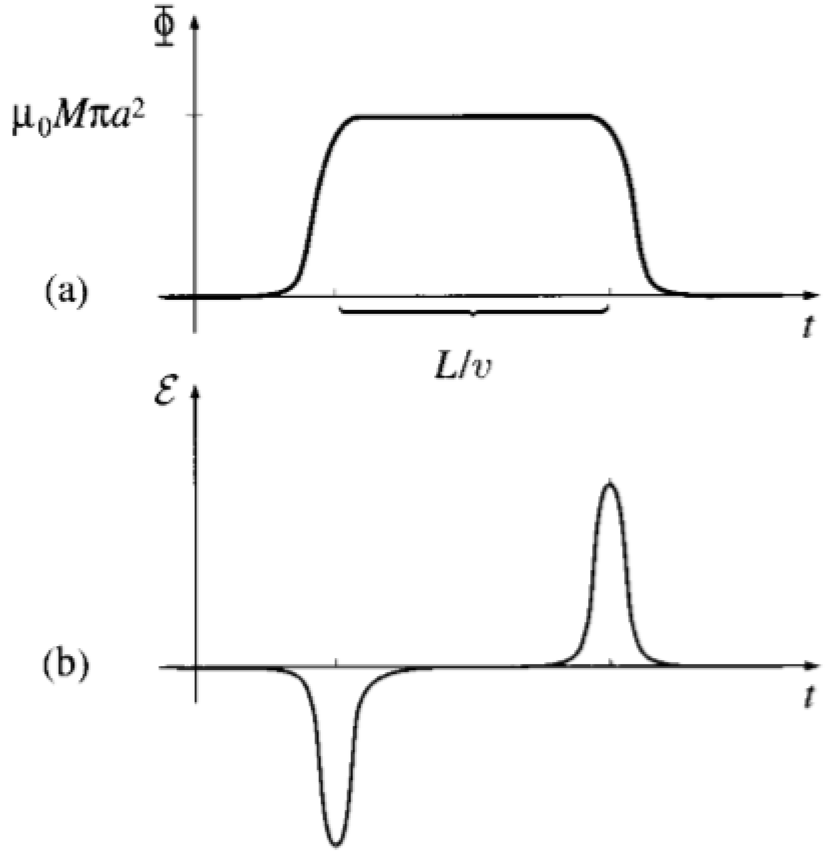

Figure 7.22

Faraday Law and Lenz's Law

Positive direction of flow of current is anticlockwise if you see from left hand side.

since the first spike in Fig. 7.22b is *negative*, the first current pulse flows *clockwise*,

This is due to Lenz's Law because this direction of current opposes the motion of magnetized cylinder

Nature abhors a change in flux.

The induced current will flow in such a direction that the flux *it* produces tends to cancel the change.

Lenz's law tell you the direction of induced current