CHAPTER 14

Stepping Motors

Although not truly "mechanisms," stepping motors deserve consideration in this book because they comprise one of the most important of all modern-day methods for producing high-speed intermittent motion. They are electrical motors that are designed to take a single step when fed a single electrical pulse. Some types of stepping motors, or *steppers*, as they are often called, will also run continuously just as a "regular" motor if the input frequency is high enough; but most steppers are not used in this way.

Stepping motors are much in favor today since a large number of industrial and commercial functions are now controlled by digital computers or other digital equipment, and the stepping motor offers an excellent method of converting electrical pulses into various types of motion. Of course, such things as solenoid operated ratchets, clutch and brake systems, inverse escapements, etc., can also serve the purpose and are used to produce motion from pulses. The step motor, however, can operate at much higher speeds (thousands of steps per second in some cases) and with a much longer life than an impacting mechanism such as a ratchet. One of the most significant advantages of most stepping motors, in fact, is the absence of contact impact between input and output members. Accelerations and decelerations are comparatively gentle, extending the life of any machine which is driven by the device (see Fig. 5–6).

Advantages and Disadvantages

High speed, absence of impact and very long life are the principal advantages of the stepper. Another advantage, in some applications, is its versatility. Dwell and motion periods can be as long as desired (if the motion period includes one, or more than one, step). Steppers are frequently used, therefore, in systems where the dwell period or length of motion is expected to be variable; in digital process control systems, for example, where they might be used to position valves, etc.

Stepping motors are also very compact drive systems (compared to motor-clutch-brake combinations, for example). We tend to overlook the fact that a cam or Geneva must be driven by something. The cam looks small and compact, but the total intermittent motion drive system also involves a motor. With a stepper the "motor" is the whole system (except for the control circuits, of which some type is also required with "regular" motors).

Stepping motors are generally used in an open loop control system. There is no feedback since none is required, presumably, to position the load. If the stepper is fed five pulses it will move to a new position five steps beyond the first. Some designers, however, insist that it is very dangerous to count on this if your personal safety or the safety of your machine depends upon the certainty that the motor has obeyed you. Digital pulses have a way of getting lost or of appearing when least expected (thanks to electrical "noise").

Many designers, therefore, provide the stepper system with a feedback of some type; perhaps a shaft encoder on the load that is checked by the digital computer which has given the original instructions to the stepper. Even then some designers still prefer an analogue system (servo loop) to a digital system because of the ever present "noise" problem.

The stepper is usually a very elastic drive since in most types there is no mechanical contact between rotor and stator. Forces are generated electromagnetically; this eliminates impact and makes possible a very long life, but it also means that the torque applied to the output shaft is elastic. This is a "springy" drive, and care must be taken to control hunting and vibration as a result. Dampers or brakes must be used in many situations.

Step motors also need rather complex drive circuits since most of them require two or more separate trains of input pulses and these various pulse trains must be properly phased with relationship to each other if the motor is to operate correctly. For the highest speeds under the highest loads, furthermore, there is an acceleration and deceleration phase during which the pulse repetition rate must be lower than the maximum that the motor can follow. This requirement further complicates the drive circuits. Finally, there is frequently the need to modify the drive circuit to "force" the motor coils and/or to energize the coils in a pattern that will increase the locking or holding torque, reduce vibration or hunting, etc.

As a result of all this, step motor drive systems can be quite expensive compared to the drive circuits for such mechanisms as ratchets and inverse escapements; but, of course, neither of these latter devices have the versatility of the stepping motor, hence a pure cost comparison is really not fair.

Magnetic Circuits—Some Basic Principles

Most engineers have not had much exposure to magnetic circuits (as opposed to electrical circuits), and it would probably be helpful to take a look at some basic principles before studying the specific configurations of various types of stepping motors.

Figure 14–1 shows a simple magnetic circuit and its electrical equivalent. An electrical coil is wrapped around one leg of a magnetic circuit which is comprised of three pieces of iron and an "air gap." There are also very small "air gaps" where the various pieces of iron are joined together. When the coil is energized, perhaps by placing a battery across its terminals, the coil will generate magnetic flux. This flux will seek the path of least resistance from one end of the coil to the other, and so will "flow" in the pieces of iron that comprise the magnetic circuit, just as electrical current will flow in a copper wire that connects the two terminals of a battery in an electrical circuit. In each case the metal is a lower resistance path than the surrounding air. To be rigorously accurate, we must recognize that magnetic flux will not confine itself completely to the iron but will also travel, to some extent, outside the iron (leakage flux). We can safely ignore this in the analyses which follow, however. In the magnetic circuit above, the flux is also forced to travel entirely in air for part of the way, through the three "air gaps." Air gaps reduce the amount of flux a given magnet can produce in a magnetic circuit, just as a resistor limits electrical current. The large air gap will have quite a bit of resistance to the build-up of flux. The small air gaps will also resist it, but to a lesser extent. This resistance to the development of flux is called *reluctance* in a magnetic circuit.

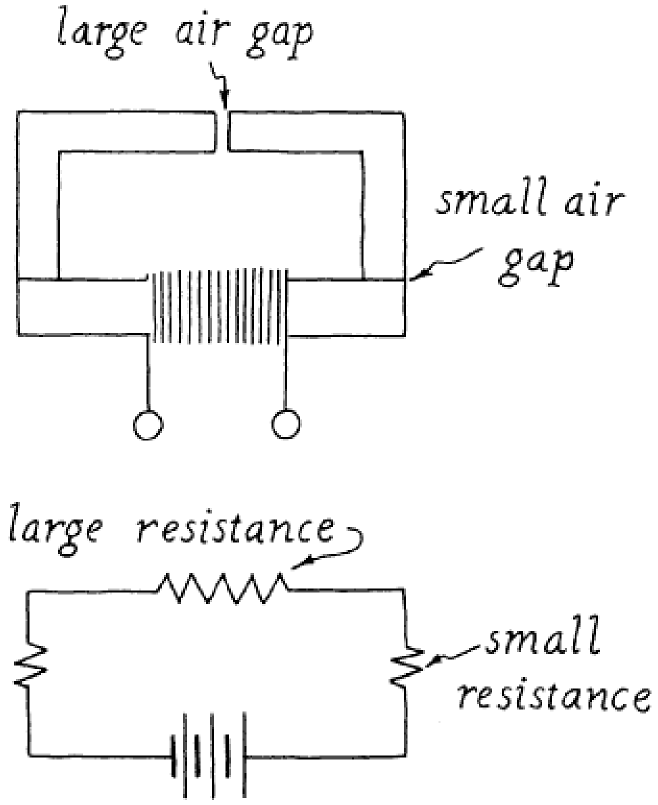

Fig. 14–1. Simple magnetic circuit and equivalent DC electrical circuit. A coil energized with direct current acts in a way that is analogous to an electrical battery; the first producing flux, the second, current.

The direct current electrical circuit at the bottom of Fig. 14–1 is an exact analogue of the magnetic circuit. A battery generates current which passes through the circuit encountering one large and two small resistors. The larger the total circuit resistance, the more difficult it is to generate current in any part of the circuit. By the same token, the larger the air gaps in the magnetic circuit, the more difficult it is

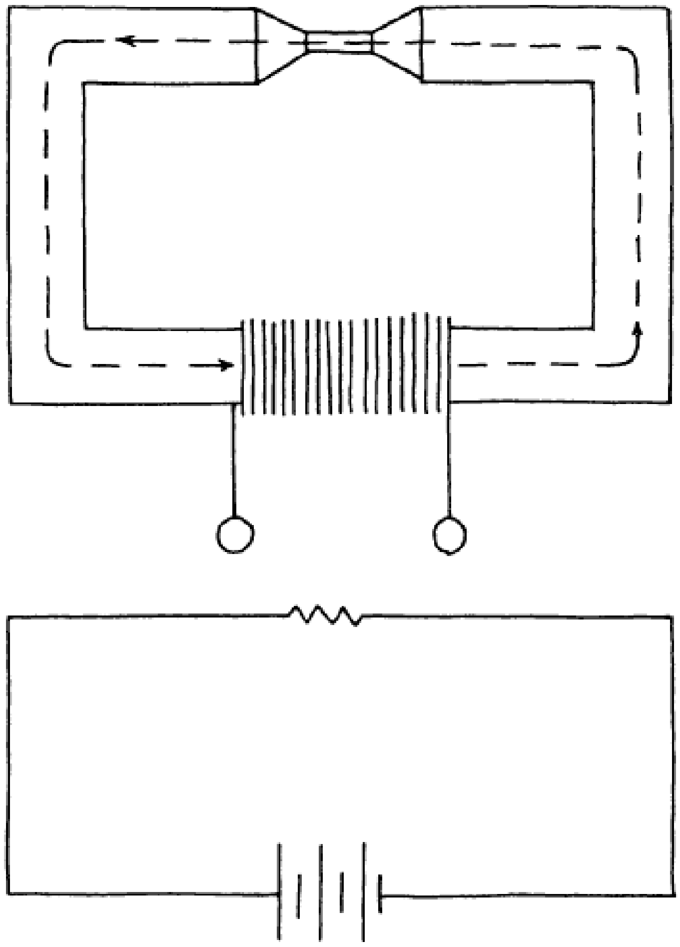

Fig. 14–2. Magnetic circuit containing one piece of iron with a reduced cross section, and equivalent DC circuit.

to generate magnetic flux in the iron and the air gaps.

Figure 14–2 shows another magnetic circuit and its electrical analogue. In this case, there are no air gaps, but part of the iron has been reduced in cross section. Since the amount of flux that can pass through a piece of iron depends, in part, on the iron's cross-sectional area, the reduced section also acts as a small resistor.

In Fig. 14–3, we see what happens when an attempt is made to drive a lot more flux through the circuit of Fig. 14–2. The reduced cross section, which had previously acted as a relatively small resistor, now saturates with flux until it can hold no more. Attempts to increase the flux still further reveal that the reduced cross section is now acting as an air gap of the same length. In effect, the reduced cross section has been taken out of the iron circuit. Unlike most electrical resistors, therefore, magnetic circuit reluctances are not constant values. They change in value as the flux density changes.

A parallel magnetic circuit and its electrical equivalent is shown in upper diagram of Fig. 14–4. The flux generated by the electrical coil now divides between two branches of the magnetic circuit just as the electrical current in the circuit (lower diagram) divides between the two legs of the electrical circuit. In each case, the amount of current (or flux) is dependent upon the amount of resistance (or reluctance) in the circuit. The left-hand leg of the electrical circuit carries more current than the right-hand leg because resistor r_3 is a lot bigger than resistor r_1. By the same token, the amount of flux in the right-hand leg is less, because air gap g_1 in the magnetic circuit has a lower reluctance than air gap g_3. This is because the pieces of iron facing each other at g_3 are not aligned, thus decreasing the area by which the pole-faces overlap. Less area means higher reluctance (just as an increase in air-gap length means higher reluctance) and, therefore, less flux. Misalignment of this sort is always encountered in stepping motors and it is useful to know how the flux will distribute itself in this situation.

Figure 14–5 (*Left*) shows another magnetic circuit that is similar in appearance to that shown in Fig. 14–4. In this case, however, all poles are aligned.

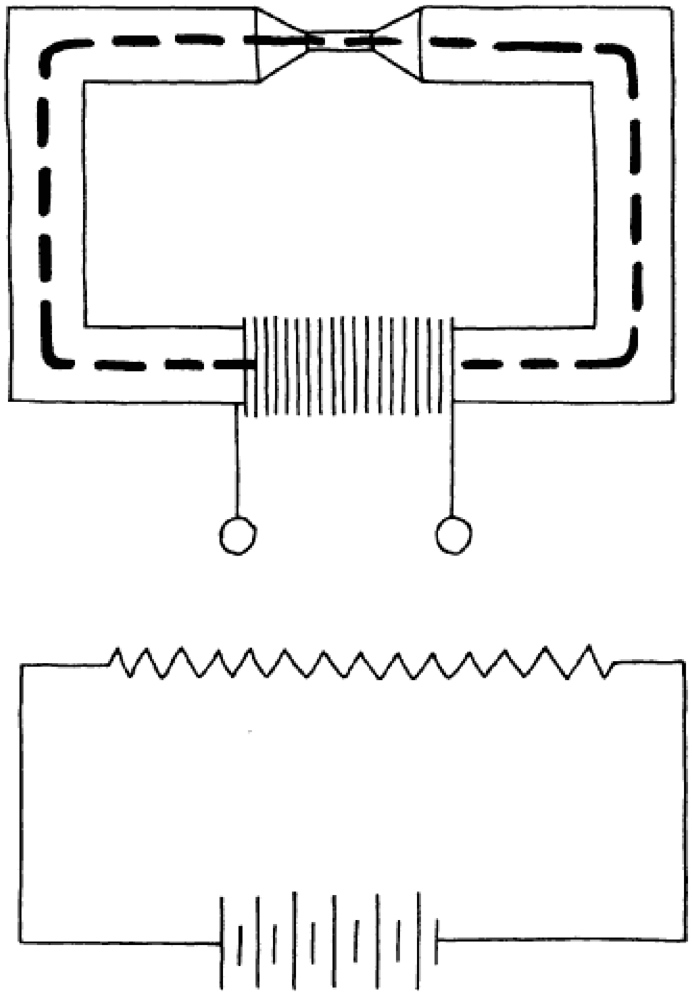

Fig. 14–3. Same magnetic and electrical circuits as in Fig. 14–2. With more current flowing in the coil more flux is generated.

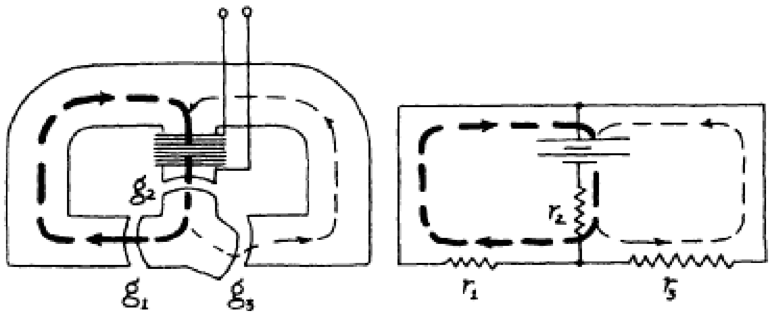

Fig. 14-4. Parallel magnetic circuit and its electrical equivalent.

Here, also, are three separate sources of magnetic flux. Two permanent magnets m_1 and m_2, and the electrical coil at the bottom. The permanent magnets are placed with their north poles on top, as shown. The electrical circuit equivalent for this magnetic circuit is shown in 14-5 (*Right*). At least this is the equivalent circuit as long as the coil at the bottom of the magnetic circuit is not energized. Under these circumstances there are only two flux producers, the two permanent magnets, and the iron loop containing the coil is, in effect, a short circuit between the two south poles of the two magnets. If these magnets are of equal strength, however, no flux will flow in this leg of the circuit; just as in the electrical equivalent circuit, no current will flow in the bottom wire as long as the two small batteries are equal.

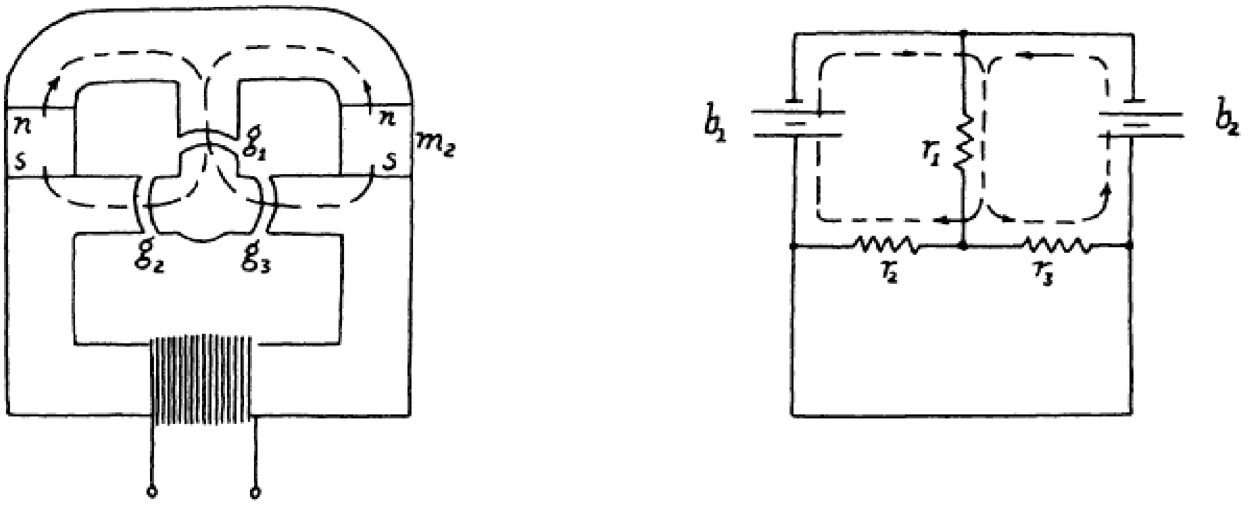

Fig. 14-5. Parallel magnetic circuit with permanent magnet and electromagnetic flux generators. (*Left*) In this illustration the electrical coil is not energized. Flux is produced only by the two permanent magnets as shown by the light dotted lines. (*Right*) Equivalent electrical circuit.

Figure 14-6 (*Left*) shows what will happen when the coil in Fig. 14-5 is energized; with a north pole to the left, and a south pole to the right. The flux developed by the electrical coil will now aid the flux produced by magnet m_1, and oppose the flux produced by magnet m_2, producing heavy flux through some portions of the circuit, as shown with a heavy dotted line, and light flux in the other legs. In the electrical equivalent circuit (*Right*) a new battery, b_3 has been added to the circuit and the current pattern is then the same as the flux pattern of the magnetic circuit.

The polarity of the electrical coil has been reversed in Fig. 14-7 so that the north pole is now on the right-hand side rather than the left. The electromagnetic is now aiding permanent magnet m_2, rather than m_1 (*Left*). Reversing the polarity of battery b_3, in the equivalent electrical circuit (*Right*), accomplishes the same thing. Notice that in both cases (Figs. 14-6 and 14-7) there is very little flux in one of the two air gaps g_2 or g_3, whereas originally (Fig. 14-5), there was equal flux in both of the gaps.

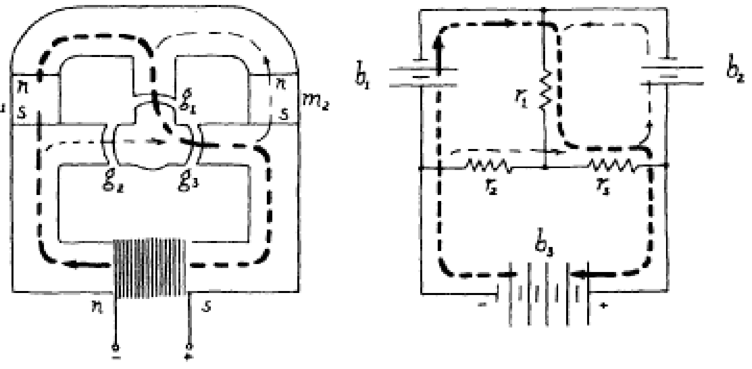

Fig. 14-6. The magnetic circuits of Fig. 14-5 with the electrical coil energized (*Left*). This coil acts to switch the flux of the permanent magnets as shown, producing heavy flux (heavy dotted line), and light flux (lighter dotted line). The electrical equivalent circuit (*Right*), behaves in the same fashion if a third battery b_3, is introduced.

Energizing the electrical coil has switched the flux so that most of it passes through one gap or the other. Flux switching of this type is encountered in many stepping motor designs.

Flux and Torque

We have seen that the amount of flux passing through a given leg of a magnetic circuit can be influenced by either air-gap length, air-gap area, or by flux-switching techniques. Now let us relate flux patterns to drive torque. In Fig. 14–8 two different electromagnetic circuits are seen. Circuit 14–8 (*Top*), is the same as the simple circuit of Fig. 14–1, but a rotatable piece of iron (hereafter called a rotor) has been inserted in the air gap. In the diagram, this rotor is at an angle to the adjacent legs of the magnetic circuit, reducing the area of overlap of the pole faces (rotor and circuit). As we have seen, a reduction in overlap area means an increase in the reluctance of the air gap. If the rotor is free to turn it will move to increase the overlap area, to reduce air-gap reluctance. And the system would do work while it turned. In other words, a weight could be hung from a pulley mounted on the rotor and the rotor would lift the weight as it moved to align its pole faces with those of the adjacent circuit.

Some people like to think of flux lines as rubber bands. Stretching a rubber band requires work. The band will do work as it "shrinks" in size. This is a useful and reasonably correct analogy for understanding the behavior of stepping motors and other magnetic circuits.

With a rotor in a magnetic circuit, torque is required to crowd flux lines through a smaller area or to increase the length of flux lines. In the circuit of Fig. 14–8 (*Top*) we could think of the "rubber band" flux lines as following the path sketched by the heavy dotted line. As the rotor turns, the dotted line shrinks in length, delivering energy to the system which provides work to move a load.

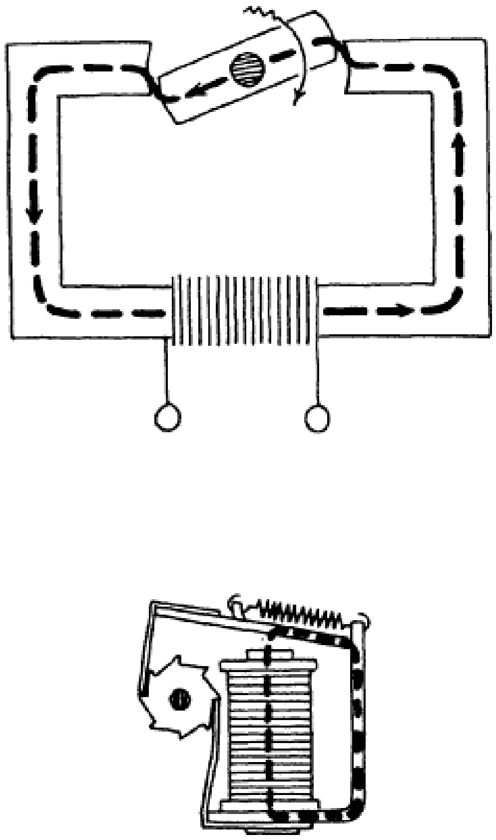

Fig. 14–8. Two different magnetic circuits. (*Top*) Simple magnetic circuit with rotor, showing stretching of flux in air gaps. (*Bottom*) Conventional ratchet motor with ratchet wheel driven as flux lines decrease in length.

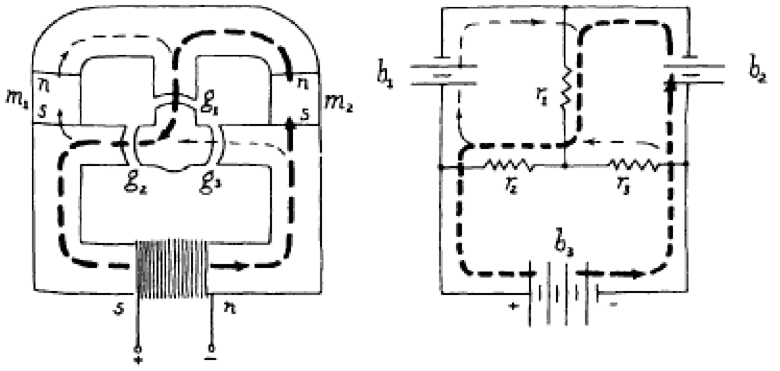

Fig. 14–7. The magnetic and electrical circuits of Fig. 14–6 with the polarity of the electrical coil (and battery b_3), reversed. (*Left*) Flux is switched in the other direction to that shown in Fig. 14–6. (*Right*) Current is also reversed.

Other electromagnetic power plants work on this "shrinking flux" principle. Something moves to shorten flux lines and the output work is taken from the thing which moves. In Fig. 14–8 (*Bottom*), as a second example, we see a conventional ratchet motor. A solenoid attracts a clapper whenever the solenoid is energized. The clapper, in turn, drives a spring blade which indexes a ratchet wheel. In this case, the "elastic band" flux lines are fairly tidy to begin with, but they do shorten as the device produces work to drive the ratchet wheel and its load. This is a more accurate rubber-band analogy than the first example, since the change in reluctance that is producing the work is a change in air-gap length rather than area. But the analogy is useful for both situations.

Stepping Motor Design

Consider now a magnetic circuit configuration that more nearly resembles a stepping motor. Figure 14–9