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,

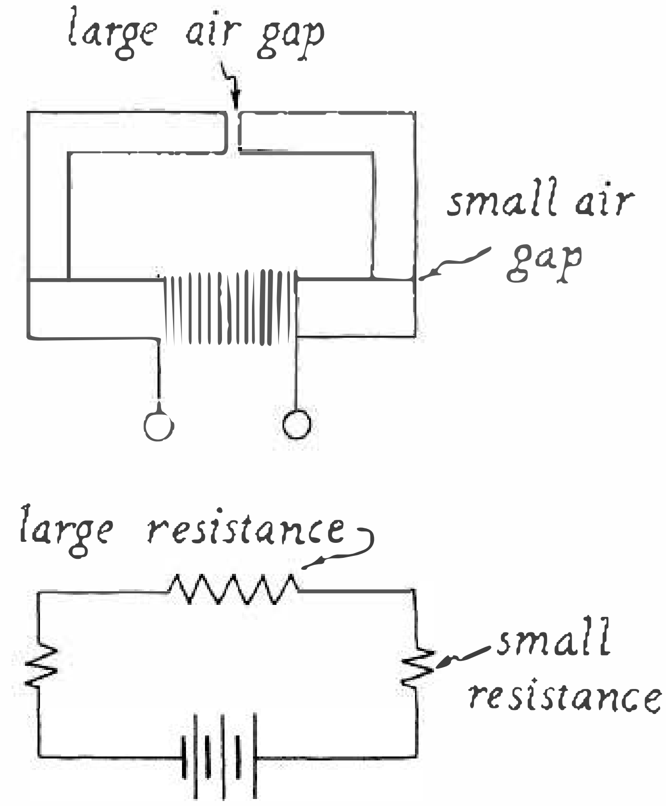


Fig. 14–1. Simple magnetic circuit and equivalent DC electrical circuit. A coil energized with direct current acts in a way that is analogous to an electrical battery; the first producing flux, the second, current.

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 buildup 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.

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

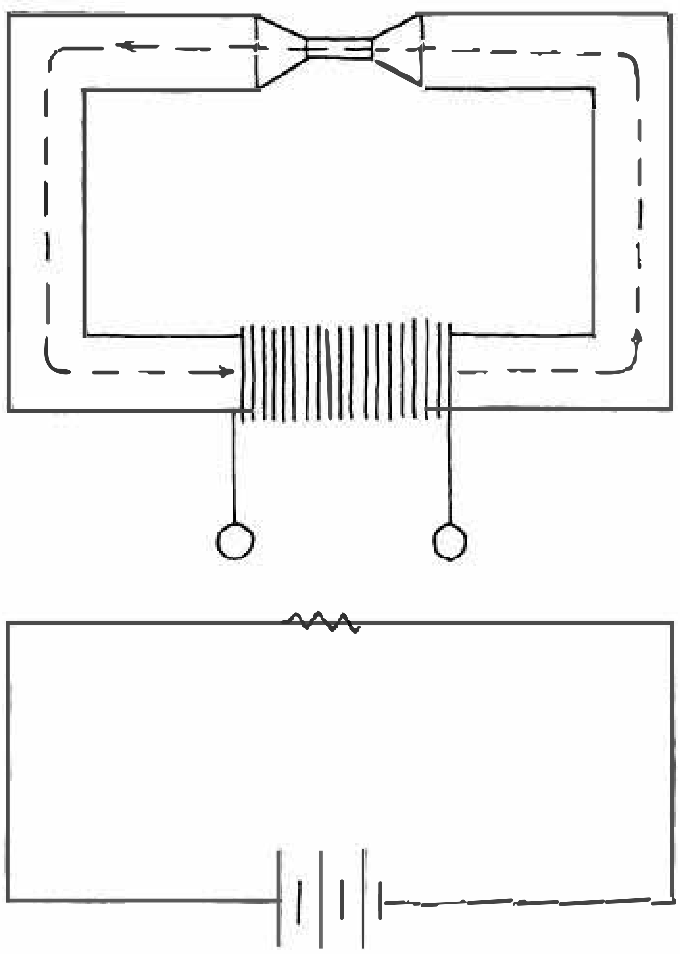


Fig. 14-2. Magnetic circuit containing one piece of iron with a reduced cross section, and equivalent DC circuit.

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_2 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.

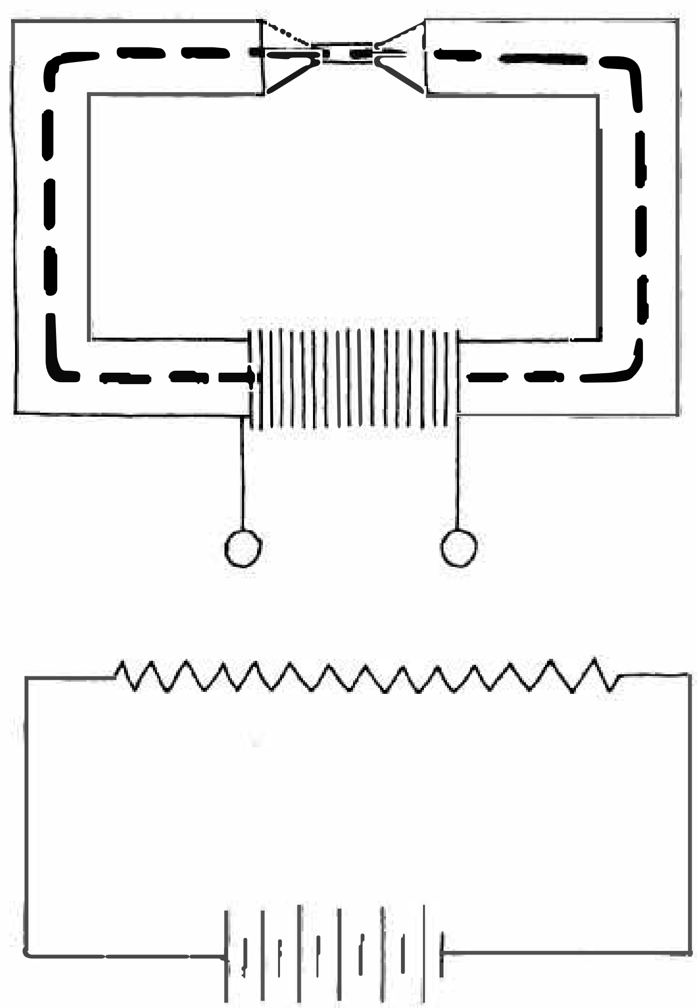


Fig. 14-3. Same magnetic and electrical circuits as in Fig. 14-2. With more current flowing in the coil more flux is generated.

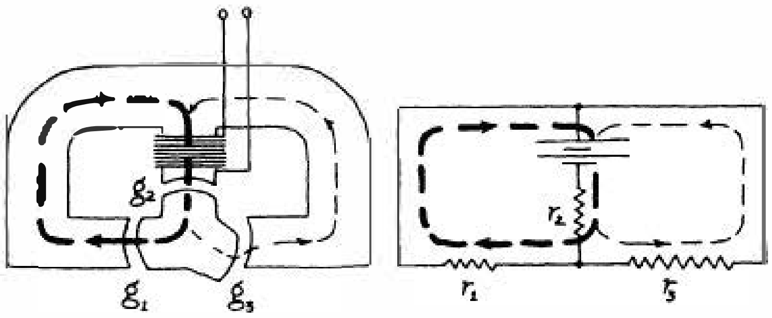


Fig. 14-4. Parallel magnetic circuit and its electrical equivalent.

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.

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.

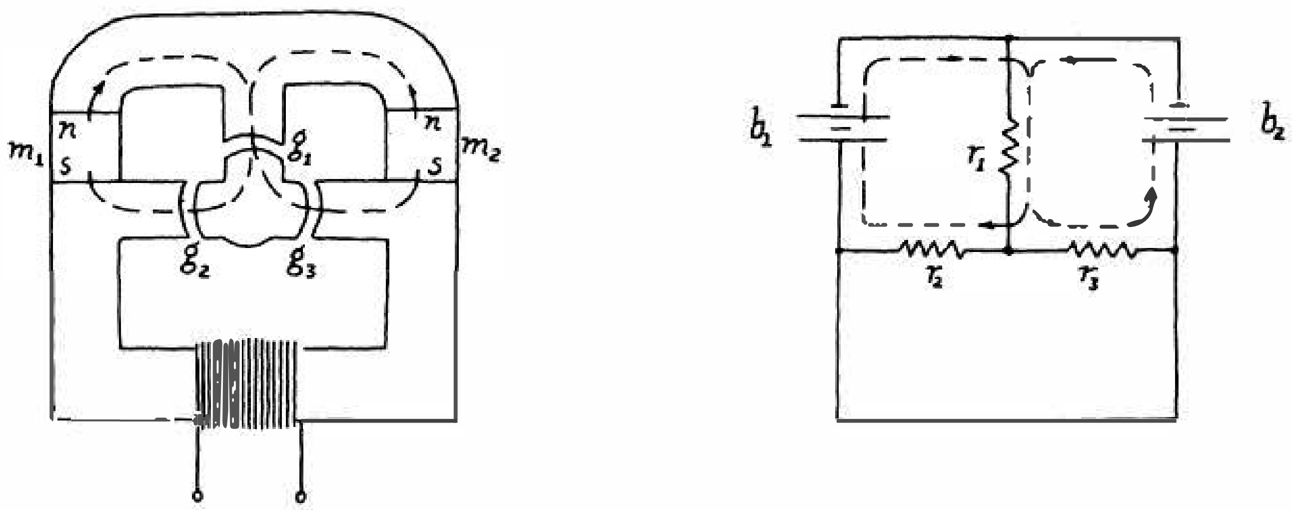


Fig. 14-5. Parallel magnetic circuit with permanent magnet and electromagnetic flux generators. (*Left*) In this illustration the electrical coil is not energized. Flux is produced only by the two permanent magnets as shown by the light dotted lines. (*Right*) Equivalent electrical circuit.

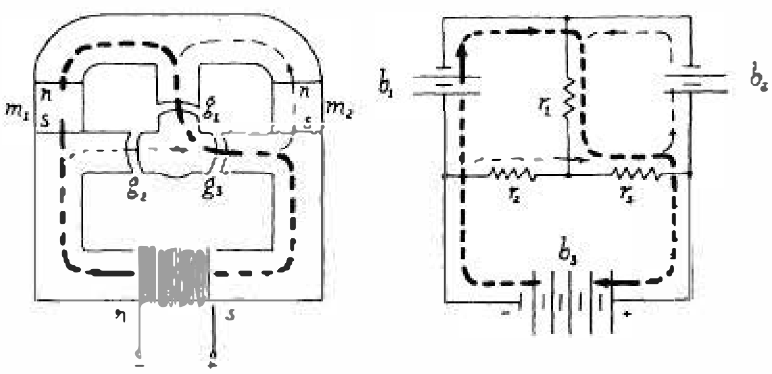


Fig. 14-6. The magnetic circuits of Fig. 14-5 with the electrical coil energized (*Left*). This coil acts to switch the flux of the permanent magnets as shown, producing heavy flux (heavy dotted line), and light flux (lighter dotted line). The electrical equivalent circuit (*Right*), behaves in the same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

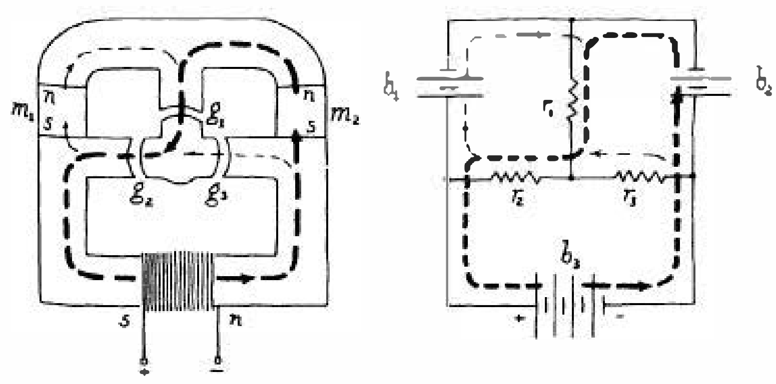


Fig. 14–7. The magnetic and electrical circuits of Fig. 14–6 with the polarity of the electrical coil (and battery b_3), reversed. (*Left*) Flux is switched in the other direction to that shown in Fig. 14–6. (*Right*) Current is also reversed.

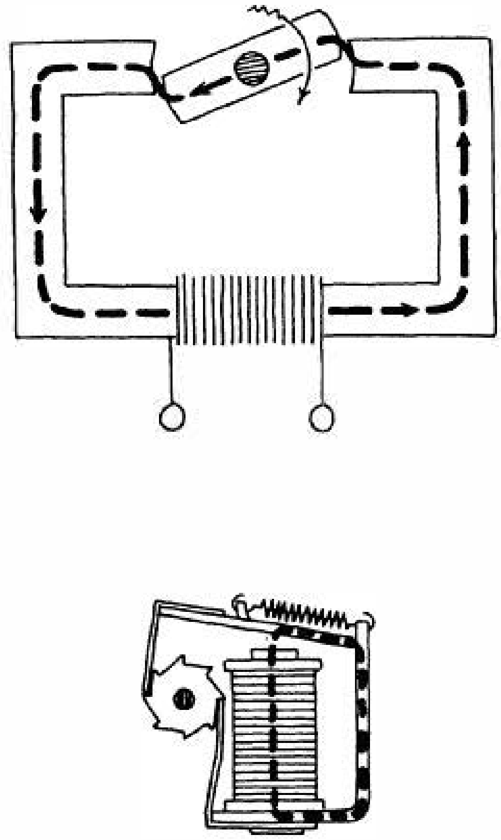


Fig. 14–8. Two different magnetic circuits. (*Top*) Simple magnetic circuit with rotor, showing stretching of flux in air gaps. (*Bottom*) Conventional ratchet motor with ratchet wheel driven as flux lines decrease in length.

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

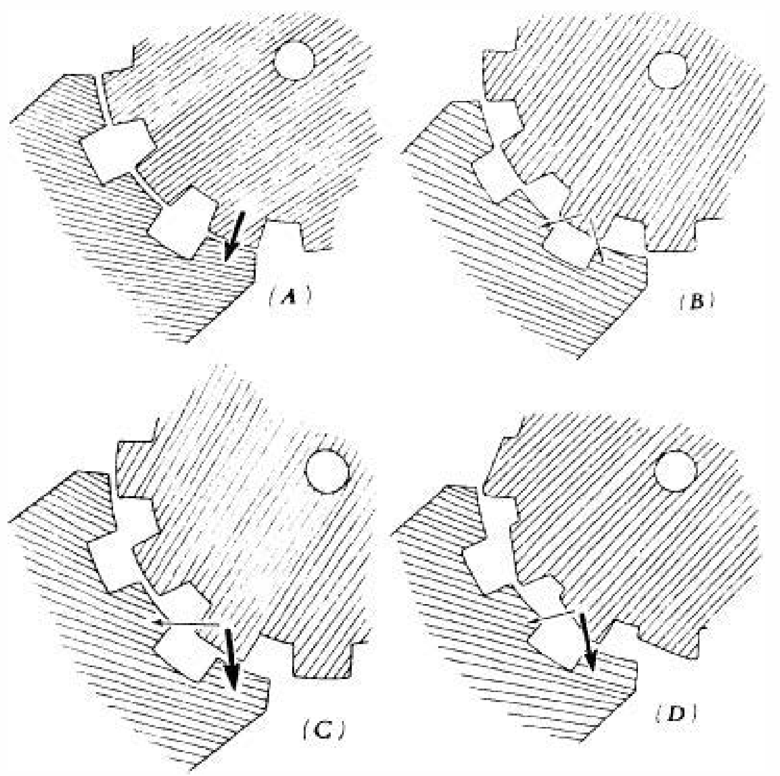


Fig. 14–9. Portions of a magnetic rotor and stator pole showing flux and torque produced in various stepping motor situations.

shows portions of a stator pole and rotor from a hypothetical stepping motor. Various possible alignments between these two members are shown in the four illustrations. Arrows indicate the intensity and main direction of magnetic force between rotor and stator in each case. A heavier arrow indicates more force than a light arrow. Although arrows are shown at only one pair of poles, force would also exist in equal measure and in the same relative direction between the other pole pairs.

In Fig. 14–9A, rotor and stator poles are perfectly aligned. This is the condition of minimum air gap and, therefore, of minimum reluctance. A large amount of flux will pass from rotor to stator, but because the poles are aligned, there is no "elastic band" to straighten at this point and no torque is generated between rotor and stator. If we attempt to move the rotor, however, a torque resisting such motion would be encountered as soon as there were any pole misalignment.

In Fig. 14–9B the rotor poles are positioned exactly halfway between the stator poles. The flux will now divide in half as it passes from rotor to stator. The air gap has increased and air-gap reluctance is high.

Again, no torque will be developed here if the rotor is positioned exactly midway between stator poles, since two stator poles will "pull" equally on each rotor pole.

In Fig. 14–9C, the rotor has been turned clockwise so that the bottom pole is more nearly aligned with one stator pole than with the other. There is partial overlap between the marked rotor pole and the middle stator pole so the amount of flux that passes from the marked rotor pole to the stator is greater towards one stator pole than to the other; just as in Fig. 14–4 the amount of flux passing through gap g_1 was greater than that passing through g_2. Under these conditions, there will be a net torque on the rotor in a counterclockwise direction. As the rotor moves, the amount of flux passing into the right-hand stator pole will increase further, and that into the left-hand stator pole will decrease until the rotor is again in perfect alignment, as in Fig. 14-9A. As was pointed out earlier, there would then be no drive torque on the rotor. Nor is there any drive torque in the situation of Fig. 14–9B, since the rotor is being pulled equally in two directions. Optimum drive torque occurs somewhere between these two conditions; perhaps in that position shown in Fig. 14–9C, where there is still some residual flux to the center pole of the stator tending to retard motion, but there is a large amount of flux into the right-hand stator pole operating with a good overlap to urge the rotor forward.

Figure 14–9D shows another way to produce a net torque on the rotor. The rotor teeth, or poles, have been modified to increase the air-gap length on one side of each pole and decrease it on the other. Notice that the rotor teeth in this case are positioned exactly midway between the stator teeth, as in Fig. 14–9B, but there is a net torque on the rotor in Fig. 14–9D because of the way that the rotor poles have been shaped.

Having explained flux patterns and torque between rotor and stator poles in a typical stepping motor, we should ask what is required to produce intermittent motion? First, there must be a torque to start a load in motion. The pole configuration of Fig. 14-9C would do that. A fraction of a second later, however, the output motion must be stopped. The rotor of Fig. 14–9C will turn until the poles are perfectly aligned, as in Fig. 14–9A. It will not stop there, however, because at that point no torque is developed between rotor and stator (and because, until that point, all torque which was developed tended to move the rotor in a counterclockwise direction). As the inertia of the rotor moves it past the perfect alignment point, however, a clockwise torque is produced, as the stator pole is being "left behind." When the two poles are misaligned by about $\frac{1}{4}$ of a pitch (distance between two stator poles) the force pattern is a mirror image of that shown in Fig. 14–9C; the flux passes mainly through one of two stator poles but is now directed so as to produce a clockwise torque.

At some point between poles, therefore, the rotor will come to rest and reverse, moving in a clockwise direction until it again passes the perfect alignment position, again stops, again reverses direction, etc. It will usually do this several times, "hunting" for the perfect alignment position. Each swing carries it through a shorter arc since friction in the load and bearings tends to damp and eliminate this oscillation at about the rest or zero torque position. Once the rotor has come to rest it should be held there by some kind of detent action. This can be accomplished by permanent magnets or by keeping the drive coils energized. This detent torque must be overcome when the rotor moves again (usually when some other pole pair has been energized) thus it is desirable to minimize the detent torque when another step is taken. Electro-magnets, therefore, which can be turned off, are better (though more expensive) detent flux sources than permanent magnets. Detent torque can also be "switched" as in Fig. 14–6, etc.

The drive sequence described above is a simple one that is used in many stepping motor situations. It is possible, however, to energize "non-operating coils" of a stepping motor to help brake and detent a rotor. This is done fairly often since most stepper designers complain that it is easier to start a rotor (and load) than to stop it.

Types of Stepping Motors—Permanent Magnet Motors

One of the more popular types of stepping motors, the permanent magnet motor, is shown in Fig. 14–10 in a schematic illustration. The rotor is a permanent magnet. The stator consists of a magnetically soft iron structure and a number of energizing coils. In the illustration none of the coils are energized and the rotor is merely attracted (by its desire for a minimum reluctance flux path) to the nearest stator poles, those marked *a* and *e*. In Fig. 14–11 coil *b* has been energized to produce a south pole and coil *f* has been energized to produce a north pole (at the ends of each coil nearest the rotor). This will produce the magnetic flux shown by the heavy dotted line. Considering the flux as an elastic band we

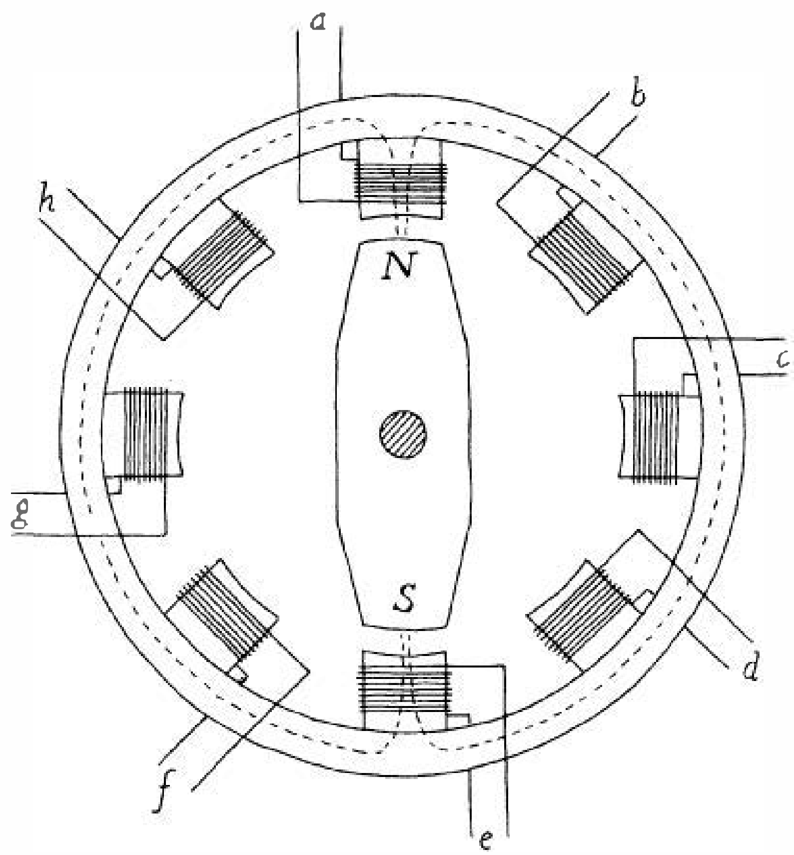


Fig. 14-10. Schematic illustration of a typical permanent magnet stepping motor. The rotor (marked *NS*) is a permanent magnet.

realize that the rotor must turn to shorten the flux lines between rotor and energized stator poles. This means that the rotor will move in a clockwise direction until it is lined up with pole faces *b* and *f*. (Again, the rotor will oscillate about *b* and *f* before coming to rest.) If we now energize coils *c* and *g* the rotor will step again in a clockwise direction. If, on the other hand, we energize poles *a* and *e* the rotor will step back in a counterclockwise direction. The motor, in other words, is reversible, depending upon the sequence with which we energize the stator coils.

The motor shown in Figs. 14–10 and 14–11 would require an "eight phase" drive circuit. In other words, we would have to energize the stator coils in the eight-step sequence, shown in Table 14–1, to produce one full clockwise revolution of the rotor.

Note that the sequence starts to repeat after eight steps. Notice too, that each coil is eventually energized in two directions, with first a north, and then a south pole at its inner end. This means that the direction of current flow in each stator pole is important and must be sequenced properly and, therefore, a fairly complex drive circuit would be required.

The permanent magnet rotor provides a detenting flux (as in Fig. 14–10) even when the last drive coil

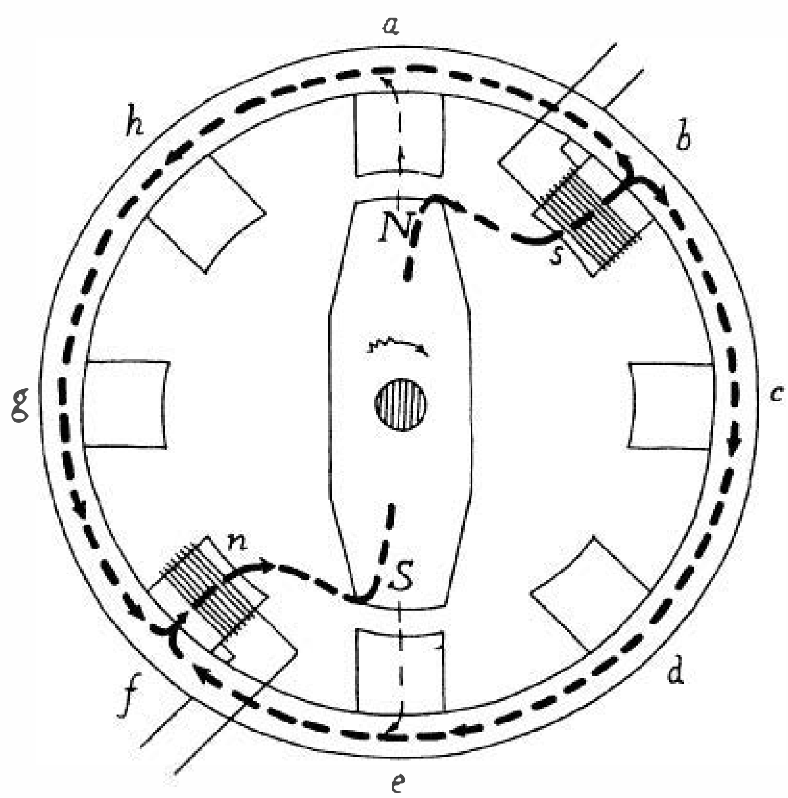


Fig. 14-11. Flux pattern produced in the motor of Fig. 14-10 when coils and *b* and *f* are energized. The rotor will move clockwise to reduce the length of these flux lines.

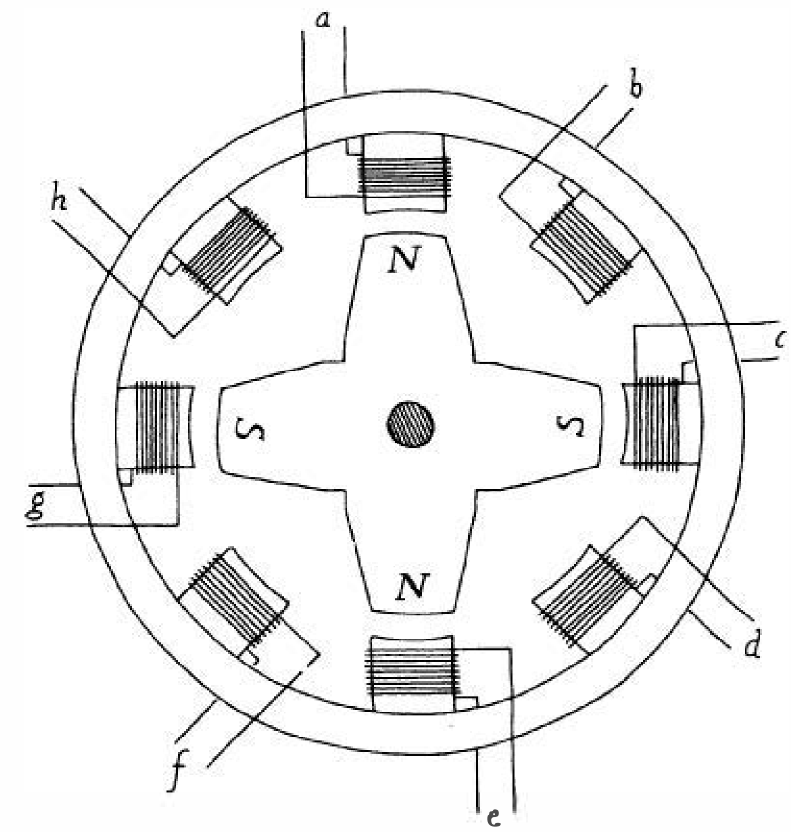


Fig. 14-12. Permanent magnet stepping motor with four poles and requiring only a four-step drive sequence

Table 14–1. Eight-step Sequence for Energizing Stator Coils in a Stepping Motor

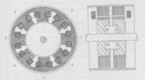
Step Number	Coil							
	a	b	c	d	e	f	g	h
	Polarity							
1		S				N		
2			S				N	
3				S				N
4	N				S			
5		N				S		
6			N				S	
7				N				S
8	S				N			
1		S				N		

is turned off. De-energized detent torque is a characteristic of most permanent-magnet steppers.

In Fig. 14–12 the rotor has been altered so that it has two north poles and two south poles instead of only one of each. The clockwise drive sequence required for this design repeats after four steps instead of eight as shown in Table 14–2.

Table 14–2. Four-step Sequence for Energizing Stator Coils in a Stepping Motor

Step Number	Coil							
	a	b	c	d	e	f	g	h
	Polarity							
1		S		N		S		N
2	N		S		N		S	
3		N		S		N		S
4	S		N		S		N	
1		S		N		S		N



Drawings courtesy of The Superior Electric Company

Fig. 14-13. End view (*Left*), and cross-section drawing (*Right*), of a large stepping motor with permanent magnet rotor.

The four-pole rotor will also produce greater drive torque, of course. By selecting the number of stator and rotor poles the designer can alter such things as torque, stepping angle, complexity of drive circuits, etc.

Permanent magnet stepping motors are generally considered to be rather simple devices, characteristically producing fairly large stepping angles with lower torque and at lower stepping speeds than can be obtained with variable reluctance motors, which will be discussed later. They do not take such precise steps as some other types, although their stepping accuracy is good enough for most applications. In general, they exhibit less tendency to overshoot than do other types of steppers, so that damping is less often required. This is, in part, because the rotor is a permanent magnet and will generate hysteresis effects and eddy currents in unused poles as it turns; this damps the motion. Rotor inertia is typically higher with a permanent magnet design than with a variable reluctance design.

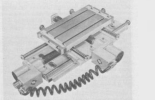
Generalities of this sort, of course, are refuted, eventually, by skillful designers. Figure 14-13 (*Left*) shows the construction of a stepping motor with a permanent magnet rotor that generates high torque, takes small steps, operates at high speed and has high resolution (good step-angle accuracy). The rotor is magnetized axially rather than radially, as can be seen in Fig. 14-13 (*Right*), the side view of this design. There are two sets of rotor teeth, one set on each end of the rotor. One of these sets is magnetized north, the other south. The two sets are angularly offset by one-half-a-tooth pitch so that as one end of the rotor is seeking north poles, the other end of the rotor can be seeking south poles. As a result, everything is working together and the device produces high torque.

Again in the left illustration, notice that the rotor is aligned with the center tooth on stator poles 1 and 5, is slightly misaligned with poles 2, 6, 4 and 8 and is seriously misaligned with 3 and 7. Four switching operations are required to advance the rotor of this design one tooth pitch. With 50 teeth on the rotor, 200 switching operations are required to produce one revolution; but there are only four different switching operations involved, thus the drive circuit is not too complex.

Figure 14-14 shows the major components of this type of motor while Fig. 14-15 shows it in use. Two motors are used to provide the X and Y drives for a machine tool indexing table.

Photograph courtesy of The Superior Electric Company

Fig. 14-14. Major components of the stepping motor shown in Fig. 14-13.



Photograph courtesy of The Superior Electric Company

Fig. 14-15. XY table for machine tool driven by two of the stepping motors shown in Figs. 14-13 and 14-14.

Variable Reluctance Motors

A different type of stepping motor is shown in Fig. 14-16; it is called a variable reluctance motor. There are no permanent magnets involved in the design shown (although permanent magnets can be used to produce some of the stator fields in certain variable reluctance motor designs). The rotor is a piece of soft iron. It has been positioned as is shown in Fig. 14–16, by energizing coil *a*. Energizing coil *b*, as shown in Fig. 14–17, will produce the flux pattern shown by the heavy and light dotted lines. (It makes no difference which direction the current takes in the drive coils.) Notice that there is a heavy flux produced in the gap between stator *a* and the rotor, but that there is no bending of the flux at this point; no rubber band to straighten out. Therefore, there will not be any torque developed between stator *a* and the rotor. There is no pole overlap between stator pole *c* and the rotor; and the air gap here is very large, thus the flux, and therefore the torque, is weak. Furthermore, the flux divides and goes in two different directions, tending to produce both clockwise and counterclockwise torques which approximately cancel each other.

Significant drive torque, however, is produced between stator pole *b* and the rotor. Here the poles overlap in such a way as to drive the rotor in a clockwise direction. As motion occurs, the flux between stator *a* and the rotor will become bent, (the poles will start to overlap) producing a torque at pole *a* which tends to retard this clockwise motion.

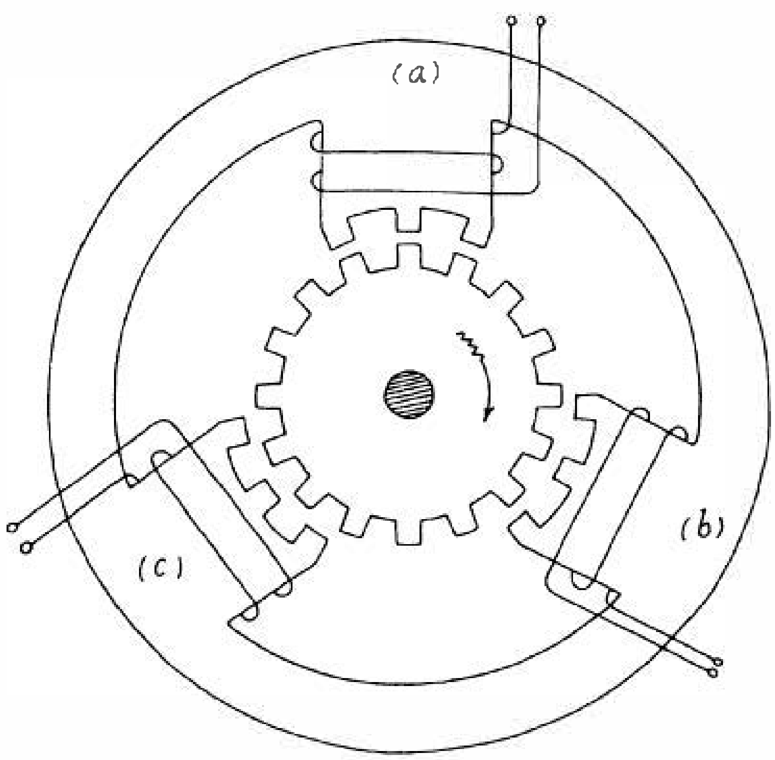


Fig. 14–16. Schematic illustration of a typical, variable reluctance stepping motor with rotor of soft iron and no permanent magnets in the design.

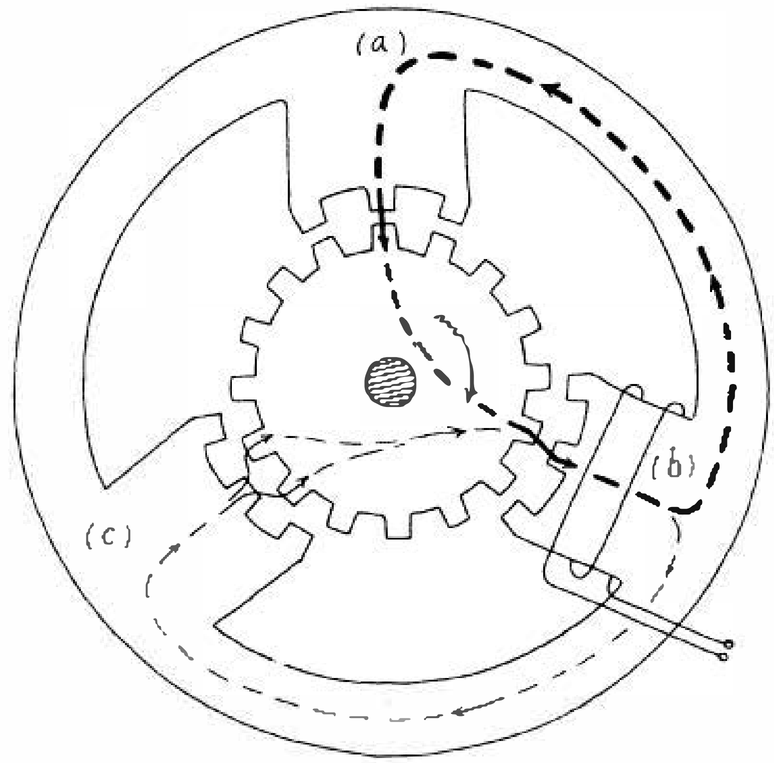


Fig. 14–17. Flux patterns produced by energizing stator pole *b*, in the design shown in Fig. 14-16.

But there is more flux at stator *b* than at either stator *a* or *c* (the combined *a* and *c* flux passes through *b*), thus *b* will dominate. As a result, the rotor will finally align itself on *b*.

Variable reluctance motors typically have small stepping angles, operate at high speeds, produce high torques, and frequently require damping. The design shown in Figs. 14–16 and 14–17 would have no de-energized detent torque, since no permanent magnets are available to provide such torque. Coil *b*, of course, could be kept energized until we were ready to energize coil *c*, and produce the next step. An "energized detent" of this type is sometimes called *holding torque* rather than *detenting torque*, since it consumes power. As pointed out earlier, however, such a detent can be turned off when it is desired to take the next step.

Electro-Hydraulic Pulse Motor

Figure 14–18 shows another configuration for a variable reluctance motor. The rotor is a disc with alternately thick and thin pie-shaped teeth. The stator poles consist of two rings also with alternately thick and thin pie-shaped teeth. The rotor-stator pole assembly is surrounded by a single electrical coil, as shown in the illustration. This coil will produce a toroidal, or doughnut shaped flux field (as shown by the dotted lines) when it is energized.

The flux lines will pass around the coil, into the stator pole ring on the right-hand side, then through the rotor disc, into the left-hand stator pole ring, and back around the electrical coil. The flux lines will seek the path of least reluctance as they pass from stator pole, to rotor, to stator pole; seeking the smallest air gaps. When the rotor is in the position shown in the illustration, the flux produced by the electrical coil will tend to rotate the rotor in a counterclockwise direction (looking at it from the right-hand end of the shaft). Once rotor and stator are aligned, however, subsequent applications of current to the electrical coil will not produce any further motion, thus this system is capable of taking only one step; and then only if it is misaligned as shown, to begin with. (See also Figs. 14–19 and 14–20.)

If five such rotors, each misaligned from the others but all fastened to the same shaft, are assembled in a single housing, however, and if the stator coils are energized in the proper sequence, a very good stepping motor can be constructed. Such an arrangement is shown in Fig. 14–19. This is a very powerful high-speed device producing one-half horsepower at speeds of up to 16,000 pulses per second. That's right, per second, not per minute!

The designers of this motor, however, have gone still further and have provided an hydraulic torque amplifier for applications requiring these extreme stepping speeds and higher output power (up to 10 horsepower). This system is shown in Fig. 14–20. The variable reluctance stepping motor is shown on

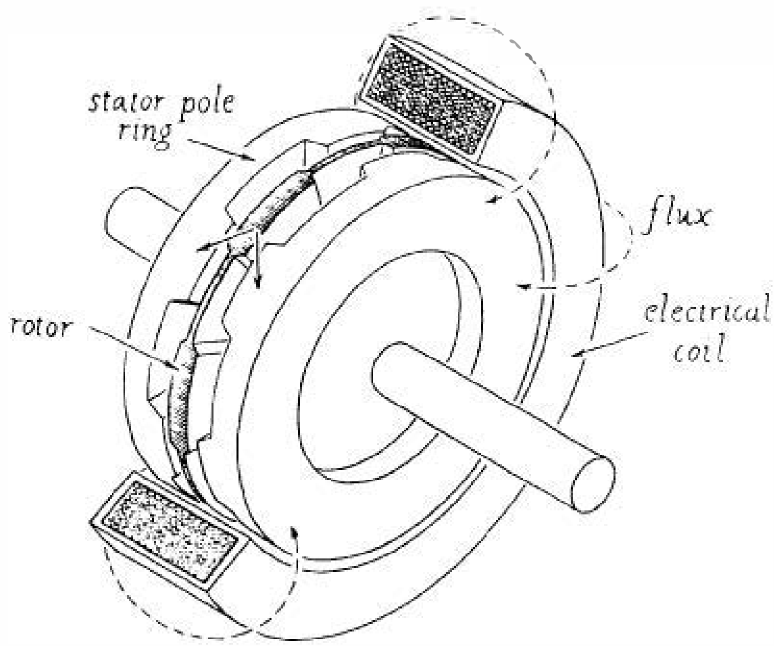
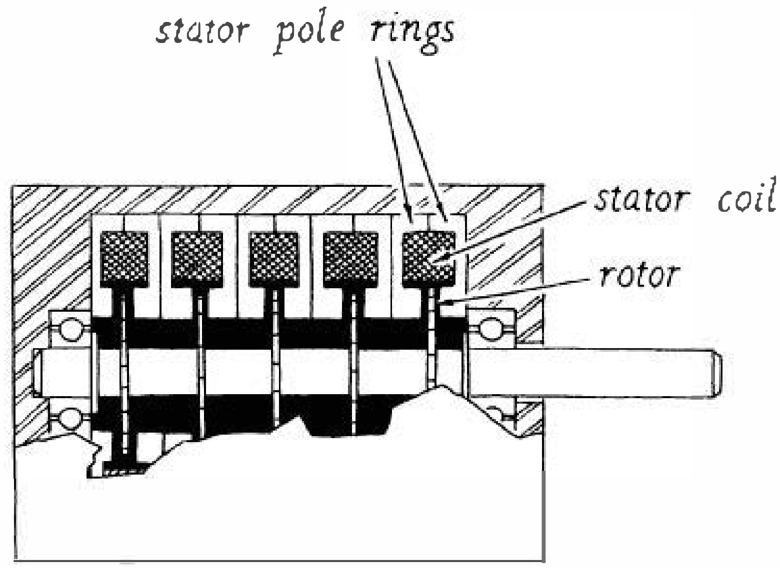


Fig. 14–18. Partial view of a type of variable reluctance motor. The section shown above would only be capable of taking a single step, and then only if initially misaligned as shown. (See also Figs. 14–19 and 14–20).



Drawing courtesy of the ICON Corporation

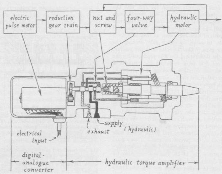
Fig. 14–19. Electrical stepping motor comprised of five of the "motors" shown in Fig. 14–18, with all rotors displaced from each other (by three degrees) and mounted on a common shaft. The stator coils are energized in sequence to produce intermittent rotary motion.

the left-hand end of the system (labeled "electrical pulse motor"). The pulse motor drives a nut and screw through a reduction gear train. The nut and screw, in turn, control a four-way valve which feeds a powerful hydraulic motor, the valve and hydraulic motor combination serving as an hydraulic torque amplifier to drive the ultimate load. An hydraulic feedback loop is provided to guarantee that the hydraulic motor accurately obeys the commands of the electrical pulse motor. The performance of this electrohydraulic stepping system is very impressive. Figure 14–21 is a photograph of one of the several models available.

Flexible Spline Motor

Figure 14–22 is a schematic representation of a very unusual stepping motor. A flexible spline is located inside a rigid ring gear. Certain portions of the spline are pulled radially outward by stator coils, to engage the ring gear. The spline has a different pitch than the stator, thus the teeth on the spline are slightly misaligned with the stator teeth, and therefore, as the spline moves outward, it rotates slightly as it aligns itself with the stator. Spline and stator teeth only engage near the energized coils as can be seen from the illustration.

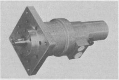
When another step is desired, another pair of stator coils is energized and a different portion of the spline engages a different portion of the ring gear. Again there is initial misalignment between



Drawing courtesy of the ICON Corporation

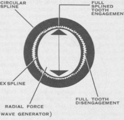
Fig. 14-20. Electro-hydraulic pulse motor. In this device the output of the stepping motor of Fig. 14-19 is amplified by an hydraulic torque amplifier with the resulting system producing up to 10 horsepower at 16,000 steps per second.

spline teeth and stator teeth (since spline and stator have different pitches), causing additional rotation of the spline. In this way, the spline is flexed and forced to rotate by sequential energization of the stator coils. The action is really very similar to that of the inverse escapement shown in Fig. 12-33, even



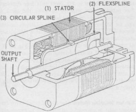
Photograph courtesy of the ICON Corporation

Fig. 14-21. Photograph of the electro-hydraulic stepping motor shown in Fig. 14-20.



Drawing courtesy of the United Shoe Machinery Corporation

Fig. 14-22. Schematic illustration of a flexible spline stepping motor. The principle of operation is very similar to that of the inverse escapement shown in Fig. 12-33.



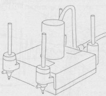
Drawing courtesy of the USM Corporation

Fig. 14-23. Cutaway drawing of the flexible spline stepping motor shown in Fig. 14-22.

though the two systems differ from each other in all important details. Figure 14-23 shows a cutaway drawing of the flexible spline stepper. Note that unlike more conventional steppers this one does involve metal-to-metal contact between stator and rotor.

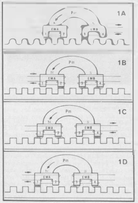
Planar Stepping Motor

Another unusual stepping motor (patented both in the U.S. and abroad) is shown in Fig. 14-24. This is a permanent magnet stepper in which the "stator" is a large table and the "rotor" is a small block that will move in either an X or Y direction (or both simultaneously) over the surface of the table. Small electromagnets are used to switch the flux from a permanent magnet, for each axis in the block, to produce the stepping motion. The surface of the table over which the block moves consists of rows and columns of square teeth as shown in Fig. 14-25.



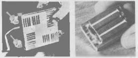
Drawing courtesy of Xynetics, Inc.

Fig. 14-24. Planar stepping motor that can be indexed in either the X or Y direction (or both simultaneously) over a "stator" table top covered with poles.



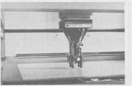
Drawing courtesy of Xynetics, Inc.

Fig. 14-25. Further details of the principle of operation of the planar stepping motor. 1A, B, C, and D—Single-axis, two-phase forcer operation.



Photograph courtesy of Xynetics, Inc.

Fig. 1[illegible] (*Left*) A [illegible] drive head from a planar stepping motor. (*Right*) Bottom [illegible] single [illegible] head.



Photograph courtesy of Xynetics, Inc.

Fig. 14-27. Planar stepping motor used in an XY plotter. Magnetic forces allow the planar motor to cling to the "ceiling" of the machine in this model.

The permanent magnet (Pm), produces equal and opposite flux in electromagnets EMA and EMB. When current is passed through EMB in the direction shown in Fig. 14-25-1A, it cancels the flux produced by the permanent magnet at pole (tip) 4 and reinforces that produced at pole 3. The walking block (or "forcer" as it is called by its manufacturer) then takes the position shown in 1A, with full alignment between pole 3 and the nearest "stator" pole. Energizing EMA to reinforce pole 2 moves the block to the position shown in 1B (Coil EMB had previously been de-energized). Next energizing EMB in a direction to reinforce pole 4 and de-energize pole 3 moves the block to the position shown in 1C; while [illegible] the position shown in 1D. [illegible]te that four different flux patterns were required to move the block a [illegible]e equal to one stator tooth, a high resoluti[illegible] can be [illegible], therefore, with relatively coarse statorteeth. A complete drive head fro[illegible] planar stepping motor (*Left*), and (*Right*) the underside of one of t[illegible] shown [illegible] Fig 14-26 The completed motor, driving a stylus on an XY draft[illegible] shown [illegible] Fig 14-27. In this particul[illegible] the motor n[illegible] only walks [illegible] an X and [illegible]irection over the large table, but does [illegible] upside down. The table in this case [illegible] a ceiling! Quite a gadget

[illegible]

Figure 14-28 [illegible]s another type of [illegible]g motor, [illegible] one [illegible]n ratchet motor A cutaway [illegible] of th[illegible] pa[illegible] design was seen [illegible] Fig. 7-34, [illegible] the chapter on ratchet mechanisms Of small size and offering very high torque at low cost, [illegible] has [illegible]s place, but [illegible] advantages and disadvantages, operat[illegible] features, etc, are those of a ratchet motor subject to impact [illegible]ion, mechani[illegible], etc. It cannot therefore [illegible] consider[illegible] stepp[illegible] motor [illegible] will no[illegible] be further discussed here.

[illegible]

When a permanent magnet, variable reluctance or electro-hydraulic stepp[illegible] motor is fed an [illegible]

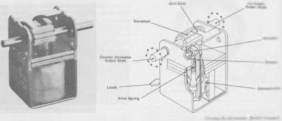


Fig. 14-28. [illegible]

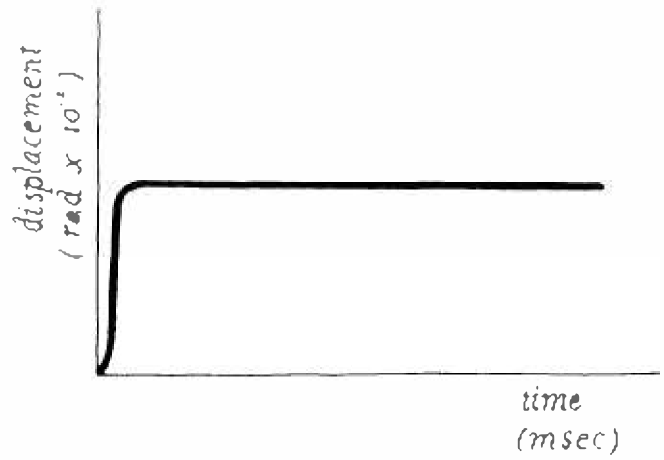


Fig. 14-29. Ideal single-step displacement curve for a stepping motor.

cal drive pulse it will take a step. Ideally, the displacement of the rotor as a function of time should be that shown in Fig. 14-29. Since all contact between rotor and stator consists of magnetic flux, (which, as has been seen, acts very much like a large elastic band), the displacement-versus-time curve is more apt to look like that shown in Fig. 14-30. The electrical pulse "impulses" the rotor which attempts to take a smooth step, but which responds (as did the impulsed block-on-a-spring in Fig. 3-19) by overshooting, then undershooting, then overshooting, then undershooting, etc., before finally reaching the new position. The response is that of a damped vibrating system to an impulse or shock input. If the damping on the output is increased, the rotor will settle more rapidly, as shown in Fig. 14-31. Various types of dampers have been proposed for this application, including mechanical devices such as that shown in Fig. 14-32, where a large inertia disc (*20*) is loosely coupled to the output shaft (*14*) of the stepping motor; the interconnection

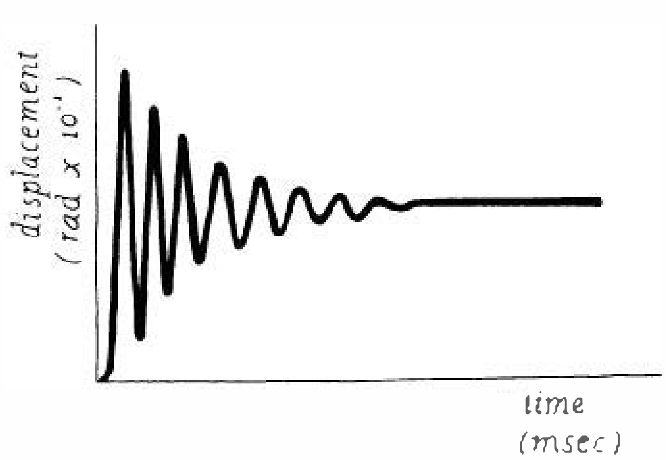


Fig. 14-30. Typical step for a conventional stepping motor. Because the only connection between rotor and stator is in the form of magnetic flux, the system responds like a vibrating spring-mass to single impulse (shock) excitation. (See also Fig. 3-19.)

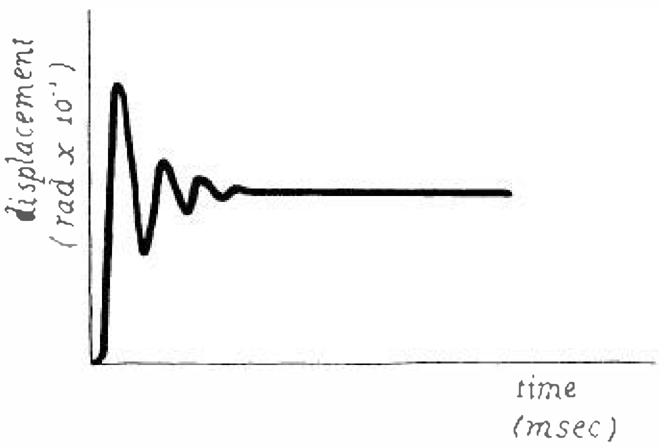


Fig. 14-31. Response of a highly damped stepping motor.

being through friction or viscous drag only. The disc will slip relative to the motor shaft, dissipating energy and damping unwanted vibrations.

Another method of damping the motion rapidly is to energize all stator drive coils simultaneously.

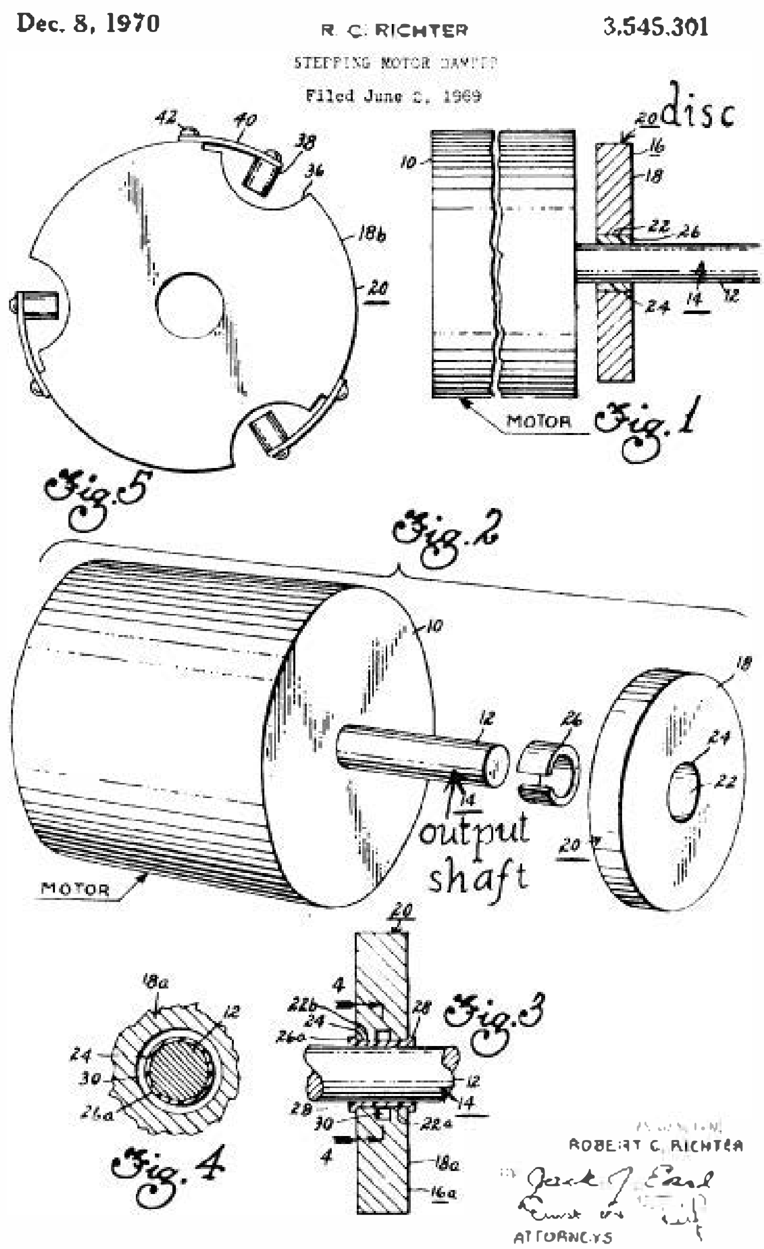


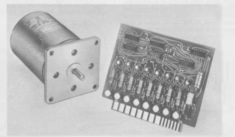
Fig. 14-32. Inertia-friction damper for stepping motor. (U.S. Patent 3,545,301; R. C. Richter.)

Photograph courtesy of The Superior Electric Company

Fig. 14-33. [illegible] stepping [illegible] One of the features of this drive unit is that it will stop the motor after a ~~predetermined number of steps have been taken.~~

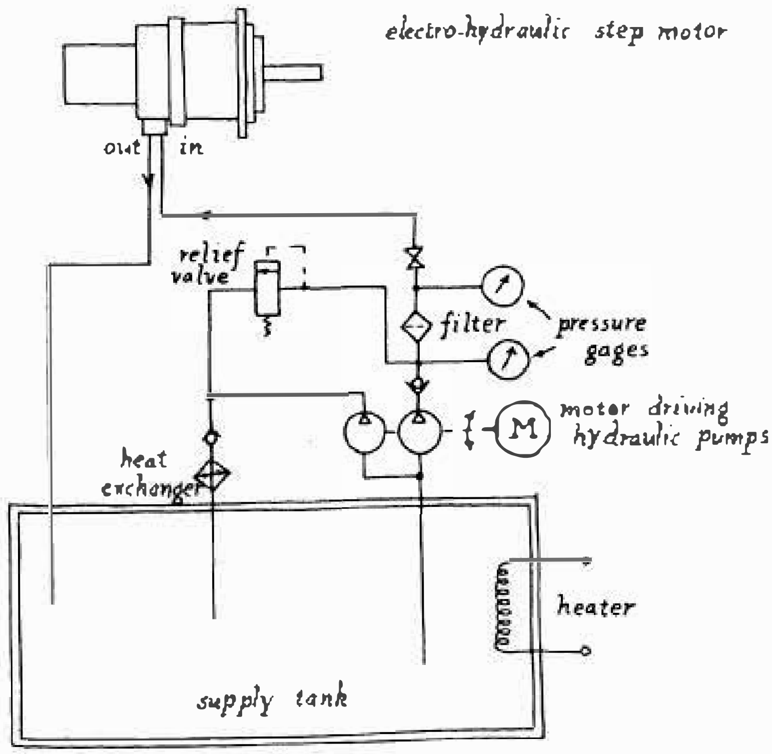
The rotor does not know which way to go and stops quite [illegible]pidl[illegible] he "unused" stator coils are energized only partially to produce a drag on the rotor rather than emplo[illegible] a complete brake action. At other times, [illegible] pulse [illegible] applied to the [illegible] winding just [illegible]fore the rotor reaches the present winding In any event, the [illegible] curves of th[illegible] ypic[illegible] stepping motor are free from shock and impact. Accelerations and decelerations are gentle compared to those found [illegible]ves ~~As a result, st[illegible] motors are frequently encoun-~~ tered [illegible] those intermittent mot[illegible] applicat[illegible] requiring high torque and ~~[illegible] stepping~~ rates.

The flexible spline and ratchet motors, of course cannot "hunt," thus their motion curves are different than those of the more [illegible] otors



Photograph courtesy of The A. W. Haydon Company

Fig 14-34. Packaged elect[illegible] circuit that [illegible] convert a single train of pulses into the appropriate coil energization sequence [illegible] pulse trains) to drive a stepping motor



Drawing courtesy of the ICON Corporation

Fig 14-35. Partial hydraulic circuit required for an electro-hydraulic stepping motor. An electrical control circuit for the electric pulse motor is also required, but is not shown here.

Drive Circuits

The design of electrical circuits is certainly beyond the scope of this book, but the intermittent motion designer should be aware that he can use many different types of drive circuits with most stepping motors. He should consult motor manufacturers for specific recommendations. Many manufacturers, in fact, sell packaged drive circuits such as those shown in Figs. 14-33 and 14-34. Some of these can be preset to stop the motor after a certain number of steps. Some start and stop the motor with relatively slow stepping rates, operating at maximum stepping rate only after the motor and load have been brought up to speed. Some motor drive circuits are intended to produce special control or damping effects, such as those described earlier. Some are designed to speed up stepping rates by "electrical forcing of the drive coils." (See Chapter 13 for further discussion of electrical forcing.) Some circuits are designed to operate a motor at minimum energy levels, others at maximum performance levels which are often produced by considerably increasing energy consumption.

Electro-hydraulic stepping motor systems require more than electrical control circuits; they also require hydraulic circuits for the torque amplifiers. Figure 14-35 shows a typical hydraulic circuit. This emphasizes, I think, that the stepping motor, like a clutch-brake combination, is a system component. Taken alone it cannot produce intermittent motion. With the proper supporting equipment, however, it can produce intermittent motion with a speed-torque capability, and with a control flexibility, unthinkable for the simpler mechanisms discussed in earlier chapters.

Anatomy of a Stepping Motor Indexing System

Following is a brief description of the components and functions of the typical stepping motor indexing system, as shown in Fig. 14-36:

A. Stepping motor; B. Friction or viscous and/or inertial damper to reduce time required to suppress motor-load oscillations between steps; C. Load; D. External controls—can be almost anything from a simple start-stop switch to a digital computer. Provides basic commands: Index, Dwell, Take 276 steps, 180 degrees, etc.; E. Digital logic circuits—probably solid state electronics but could be relays, stepping switches, etc. Converts basic commands into detailed, sequenced electronic circuit commands —for example: Start variable rate oscillator, generate 20 pulses, gradually increasing oscillator rate to 1000 pulses per second, hold at 1000 pps for 674 steps, gradually . . . etc.; F. Programmer—If stepping distance or sequence must be changed frequently it may be desirable to have a programmer to aid the logic circuits. This would probably utilize solid state electronics, but could use groups of switches, punched cards, tape or equivalent. If the program is simple and constant, it can be "hard-

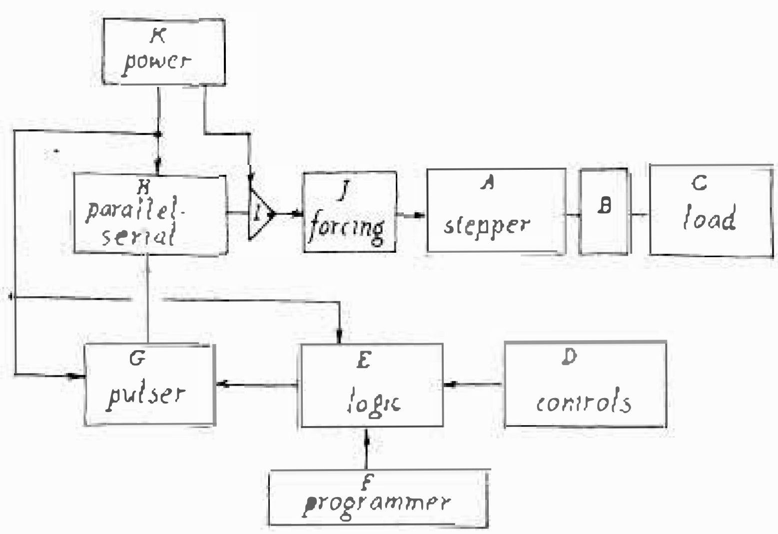


Fig. 14-36. Anatomy of a stepping motor indexing system.

wired" [illegible] the logic [illegible]s; G [illegible]te pulse generator—Logic level electrical pulses at a controllable rate to allow gradual acceleration an[illegible]f heavy loads. As an alternat[illegible] th[illegible] can be an [illegible] (magnetic or optical) pulser driven by a machine in some other part of the total system; H Serial to parallel converter—Receives [illegible] pulse tr[illegible]n from G an[illegible] into [illegible] or 8 pulse trains for the st[illegible] motor; I [illegible]fier—Receives logic level pulse trains from H and amplifies them to the power level required to drive the motor; J. Forcing circuits—Series resistors parallel capacitors, etc., for reducing the elec[illegible] t[illegible] constant of th[illegible] steppi[illegible] motor to increase step[illegible] rates; [illegible] DC power supply—[illegible] logic lev[illegible] power for [illegible] F [illegible] and H and power lev[illegible]ls for I

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Stepping motors are widely used today in machine tools and production machinery where high-speed precision indexing of heavy loads is a frequent requirement. They are, therefore, one of the latest

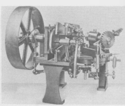

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Fig. 14-37. Robey-Smith bevel gear planar built in 1895.

types of intermittent motion devices to be used for these applications. The first mechanisms used were probably ratchets with hand-index, or manually clutched and braked indexing tables or both. Figure 14-37 shows the original Robey-Smith bevel gear planer, built in 1895. The gear being cut is positioned by a bidirectional ratchet similar to that shown in Fig. 7-16.