The Canon USM (Ultrasonic Motor) Autofocus Drive System

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ABSTRACT

Many lenses in Canon's "EF" series have autofocus drive systems described as "Ultrasonic Motor" (USM) systems. There are actually a number of different systems in this classification. This article describes the construction and operating principles of the major varieties. Included is information on the mechanisms used to allow manual focusing even with the autofocus motor drive engaged (the so-called "full time manual focus", or FTM, feature.)

BACKGROUND

The Canon EOS camera line

In 1987, Canon introduced a new line of single-lens reflex (SLR) cameras, the EOS series. The designation stands for "electro-optical system", but it was also a clever allusion to Eos, the Greek goddess of light.

The most prominent feature of the EOS line is that automatic focus (autofocus) is executed by a motor drive in the individual lens, controlled by a microprocessor in the lens, interacting with the microprocessor in the camera over an electrical interface passing across the lens mount (which is of an entirely new design).

These lenses are identified as the "EF" ("electronic focus") series.

Autofocus drive systems

A number of different autofocus drive systems have been used over the years in various EF lens models, including:

- AFD, originally meaning "autofocus drive" but later changed to "arc-form drive" when other autofocus drive systems came into use. This uses a two-phase stepping motor scheme with Hall effect detectors to provide feedback on the rotor position. The name "arc-form" comes from the fact that the stator assembly has a curved overall envelope, allowing the motor to be readily deployed in a cylindrical lens barrel. This design has not been used in new lens designs for many years.

- The micro motor (also called "DC micro motor"). Two types are used, "cored" and "coreless". Drives of this type (probably of the coreless subcategory) are used in some contemporary EF-series lenses.

- The ultrasonic motor (USM). This is used in two basic, and quite different, forms, with two variants of each. All depend on miniscule but rapid movements of metal members under the influence of the deformation of piezoelectric elements, excited at an AC frequency above the audible range (thus “ultrasonic”).

It will be this latter genre, the USM system, whose principles will be described in this article.

USM system types

USM systems are of two broad classes, the **ring USM** type and the **micro USM** type.

The ring USM type system, as the name implies, is overall in the form of a hollow ring, either 62 mm (M1 type) or 77 mm (M1 type) in outside diameter. The lens element barrel (or a small-diameter rearmost portion of it), focus cam barrel, and perhaps zoom barrel (where applicable) pass through the open center of the ring.

The drive is actually a sandwich of several rings, one or more of them rotating around the lens axis. One of those delivers the unit output, at a modest rotational speed. It is directly coupled to the focus cam barrel, no intermediate gearing being required.

In the micro USM type system, the motor itself is a small cylindrical unit, 11 mm in diameter and either 26.7 mm (original micro USM) or 13.4 mm (the newer micro USM II) in diameter. Its output is also at a modest rotational speed. It is coupled to the focus cam barrel through a simple gear train, but no large reduction ratio is involved.

Full time manual focus

All EF-series lenses have a selector switch for changing the operational mode between manual and automatic focus (MF and AF). In the MF mode, the automatic focus function is discontinued, although a portion of it remains in effect for *focus confirmation*, in which an audible-visual indication is given when the autofocus detector system believes that the current state of focus is “correct”.

In lenses not using any form of the USM drive system, and in most lenses using the micro USM motor, the selector, in the MF position, also slides a gear in the drive system to disengage the path from the motor to the focus cam barrel. This prevents the motor from imposing a “drag” on the manual focusing movement (indeed, some motors are strongly “braked” when idle and could not be readily moved when in that state) and eliminates any possibility of distress caused to the drive train by forcing the motor to follow the manual movement.

In many lenses with a micro motor drive, the micro motor is not permanently braked after the end of the autofocus process plus a modest “brake dwell” time. Accordingly, it is generally quite practical to turn the manual focus ring with the selector in the AF position, the motor just following along. There is a perceptible, but not bothersome, drag from the motor. Canon, however, discourages such operation on the grounds that it abuses the motor gear train.

In all lenses of this class, when the focus cam barrel is being moved automatically by the motor system, the manual ring turns as well (sometimes a nuisance to the photographer, who may try to support the lens by grasping it in the region of the manual focusing ring).

In all lenses with ring USM drive, a feature called *full time manual focusing* (FTM) is provided. It allows the photographer, even when the selector is in the AF position, to turn the manual focusing ring and change the focus setting without interference by, or the risk of damage to, the motor drive system. A further advantage is that while the focus cam barrel is being moved automatically, the manual focusing ring does not turn.

This feature is provided in two different ways in various of the ring USM drive lenses.

In a single lens model using the micro USM drive, this functionality is also provided.

The various mechanisms for providing the FTM feature will be described in later sections of this article.

THE RING USM DRIVE

History

Canon introduced the ring USM drive on its EF 300 mm f/2.8L USM lens in 1985. The mechanism, the traveling-wave ultrasonic motor (TWUSM) was invented by T. Sashida of Shinsei Co. Ltd. of Japan in 1982. Shinsei licensed the ensuing patent to Canon.

In addition to the use of the principle in lenses, Canon also offers a wide line of ultrasonic motors for industrial, scientific, and consumer goods applications.

Principle of operation

The motor itself comprises two open metal rings, the *stator* and the *rotor*, which are held in contact by a wave-washer spring. (There are other rings in the "stack", all held in mutual contact by that spring.)

On the side of the stator away from the rotor, there is a resilient "pad" supporting multiple piezoelectric elements (figure 1). These elements, made of a special type of ceramic, deform when an electrical voltage is applied across them (via thin electrodes plated on the element surfaces). They are in two groups; the circular spatial phase of the two groups differs by half an element pitch (the red line helps us see that).

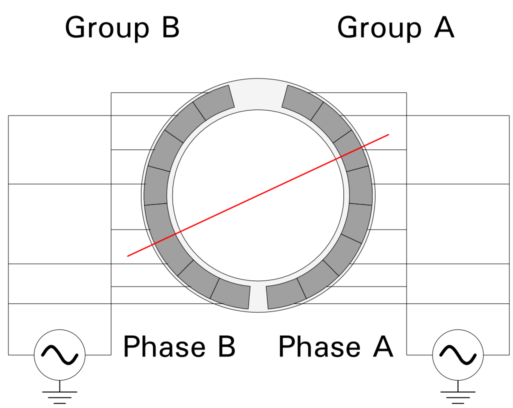

Figure 1. Ring USM piezoelectric array

The two groups of elements are electrically excited by a two-phase electrical system, which deforms the stator into a wave shape, with the wave progressing around the ring (a traveling wave). The stator itself does not turn, but merely undulates as the wave progresses. The details of how this happens are discussed in Appendix A.

The electrical frequency applied is such that the progress of the wave is at precisely the natural mechanical resonance of the stator in a particular "undulating" mode of vibration. Typically, the frequency of the excitation is about 30,000 Hz.

In figure 2 we see the stator and rotor as if they were straightened out. The axis of the rings (before they were straightened out) runs vertically in the drawing.

The face of the stator that contacts the rotor is actually composed of multiple teeth of a generally-pyramidal shape.

The undulation of the stator is shown greatly-exaggerated to most clearly illustrate the principles involved. In reality, the peak amplitude of the undulation is on the order of only 0.001 mm.

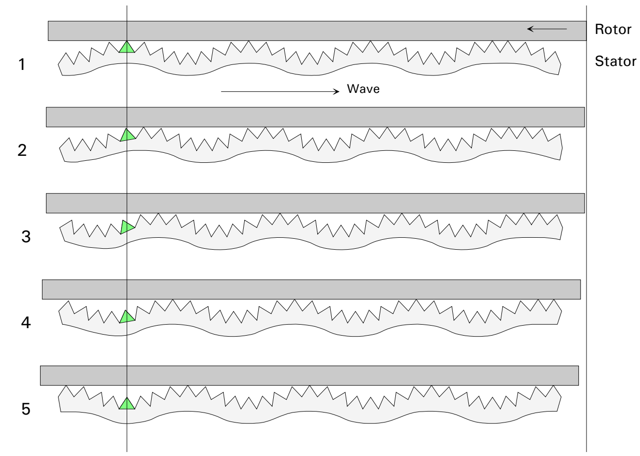

Figure 2. Principle of ring USM motor

In the successive panels of the figure, we see snapshots of the wave's progress at instants of 1/8 the time it takes for the wave to progress by one cycle. We have "painted" one tooth green, and drawn a fixed vertical reference line, so we can see that indeed the stator itself does not actually rotate.

Although the amplitude of the undulation is very small, the mating surfaces of the stator and rotor are lapped to be extremely flat (when undeformed) and smooth, so in fact there is contact between the two at the peaks of the undulation of the stator and not elsewhere.

The path of the tooth tip

On figure 2, we can see that, although our little green tooth does not progress, it does lean back and forth as the stator undulates. In figure 3, we look at this a little more closely.

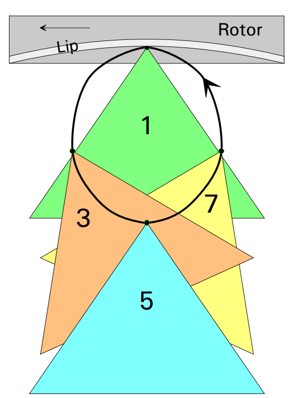

Figure 3. Tooth tip motion

We see this same tooth in its positions at instants 1, 3, and 5 of figure 2 and in a later position (not shown on figure 2) corresponding to instant "7". (I've only shown the tooth at every other instant to keep the drawing from being cluttered too much.) We note that the tip of the tooth describes a roughly-elliptical path in space.

The figure shows the lower part of the rotor. We can see that the tip of the tooth engages the rotor during a part of its motion in which it is traveling to the left, but not in any part of its motion in which it is moving to the right.

We have the same thing happening (in different time phases) at all the other teeth. Thus the rotor is urged continually to the left by the cilia-like movement of the teeth, albeit by a very tiny amount for each cycle of the wave motion.

Note that the direction of this motion is opposite to the direction of motion of the wave. In figure 2, we can see the motion of the rotor from instant to instant by noting the position of the end of the rotor segment we observe against the reference line at the right end of the figure.

At the peak of its projection, the tooth tip extends beyond the nominal face of the rotor. The part of the rotor that the teeth actually contact is a resilient “lip” on the rotor, and it deflects to accommodate the “overthrust” of the tooth tip, as suggested in figure 3. We see this arrangement in figure 4. It shows both stator and rotor in section.

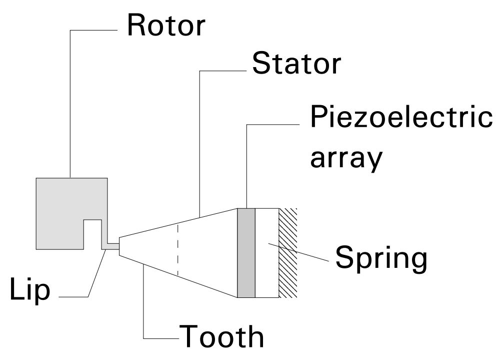

Figure 4. Resilient lip on stator

Because of the tiny motion of the tooth tips for each cycle, even with the wave rotating quite rapidly around the stator, the speed of the rotor is modest. Thus the rotor can be directly coupled to the focus cam barrel, no intermediate gear reduction being required. The available torque is quite substantial.

Typically, the rotation of the rotor with continuous excitation is at a rate of perhaps 80 rev/min (about 480 degrees/sec). When slower speeds are needed, the microprocessor applies the excitation for a brief period, then pauses, and so forth. The rate of this modulation is itself so rapid that the movement of the rotor seems continuous, but its average speed is as low as is needed.

Full time manual focusing (FTM)

All Canon EF-series lenses with a ring USM drive afford full time manual focusing (FTM). The object of this is described above.

In a few of these lenses,[1] the FTM is electrical. The manual focusing ring carries a position encoder. When the ring is turned, the output of the encoder changes, and the microprocessor in the lens responds by causing the motor to move the focus cam barrel accordingly.[2]

In most EF lenses with ring USM drive, the FTM functionality is provided mechanically by a *differential mechanism* ("differential" for short).

Functionally, the purpose of the differential (in this use) is to take two rotary inputs—the output of the USM motor itself, and the movement of the manual focusing ring—and sum them algebraically[3], using the result to control the position of the focus cam barrel.

We'll sneak up on this gradually.

Figure 5 illustrates the basic principle involved, in an abstract context:

$$y = \frac{x + z}{2}$$

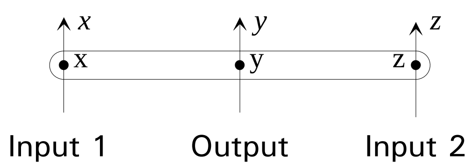

Figure 5. Differential mechanism principle

Here, the "mechanism" is just a simple lever, and we think in terms of very small movements. Three points on the bar ("nodes") are defined as **x**, **y**, and **z**; their vertical movements are the variables x, y, and z. The vertical positions of the left and right nodes, **x** and **z**, can be thought of as two inputs to the differential (although any two of its "nodes" can be thought of as inputs). We consider the vertical

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[1] A few of the current lenses. A number of now-discontinued lenses also had this.

[2] Canon's technical information office says that this is not really FTM, and that term should be reserved for lenses with the mechanical FTM system (to be described shortly), on which focus can be done even with no power to the lens. However, most Canon literature describes this electrical scheme as a form of FTM.

[3] There may be scaling factors involved.

position of node **y** to be the output of the differential. Its movement, *y*, is half the sum of the movements of the input nodes, *x* and *z*.

In fact, our identification of the three “ports” of a differential as inputs or outputs is arbitrary, derived from the use we are putting it to. Note for future reference that if we are not making any movement of one of the inputs, it must be held stationary, or it can become (unwantedly) an output.

If we just let node **x** loose when we do not mean to move it, then if there is any "load" on the output (we are using it to move something, for example), a movement of node **z** (as an input) will just cause node **x** (supposedly an "input") to become an output and move in the opposite direction, presumably not what we want in this scenario. (This is called "reaction" movement.) In actual applications of this concept, we will see the steps that are taken to avert this complication.

In figure 6 we see an actual mechanism that will exemplify the differential principle shown abstractly in figure 5, in this example for linear movement. It is sometimes called a “wheel carrier” differential.

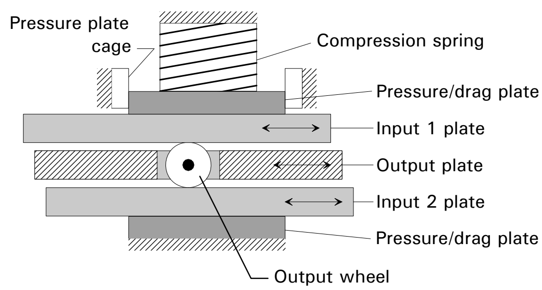

Figure 6. Linear differential—wheel carrier type

We see three movable (sliding) plates, two for our inputs and one, sandwiched between them, for our output. The output plate carries a wheel in a small axle, residing in a hole in the plate. This type of differential is sometimes called the “wheel carrier” type. We show the output plate in section to allow the wheel to be clearly seen.

On the top and bottom of the sandwich are two pressure/drag plates, not able to slide. The bottom one is fixed to the "chassis", and the top one is pressed down by a compression spring, and caged in some way to prevent its lateral motion. The result is twofold:

- The two input plates are pressed against the differential wheel, so good frictional contact is made.
- There is frictional drag on both input plates (which avoids their moving if we should turn loose of them when not wishing to explicitly change their positions).

The diameter of the wheel running from its points of contact with the two input plates corresponds to the distance between nodes **x** and **z** of the lever in figure 1.

Thus we see that the movement of the output plate is just the average of the movements of the two input plates. Said another way, it is half the sum of their movements. Or it is half the movement of one plus half the movement of the other.

Now we will bend this setup into a circle to match the way it is deployed in a ring USM EF lens. First, to help us properly visualize this, in figure 7 we see the "output ring" (the successor to the "output plate" in figure 6).

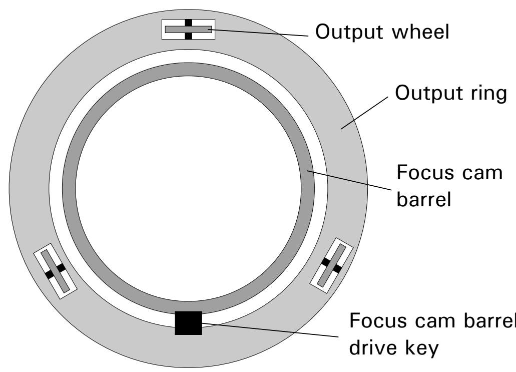

Figure 7. Rotary wheel carrier differential—output ring

Here, the output plate becomes a ring, and there are actually three output wheels (mainly to provide for a stable relationship between the layers of the sandwich when they all become rings and are pressed together).

We also see in cross-section the focus cam barrel itself, passing through the center of the output ring. The output ring is linked to it by a "drive key" (sort of a "drag link") so that if the ring rotates, the barrel will rotate as well, while eliminating the possibility of "binding" that might arise if the barrel was just rigidly attached to the interior of the ring (since each member rotates in its own "bearings").

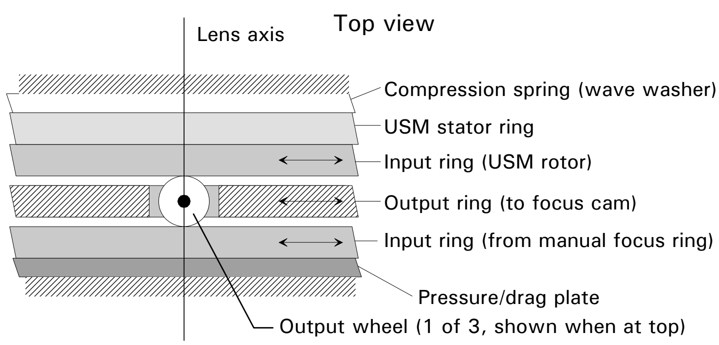

Figure 8. Rotary wheel carrier differential

In figure 8 we see the whole rig in schematic form.

We are looking down on the whole system, and we see only parts of the rings, including the part of the output ring where one of the output wheels is now (right on top). The output ring is shown in section to allow the wheel to be most clearly seen.

Toward the top of the figure we see the stator of the USM motor, which does not rotate.

In this example, we assume that the upper input ring is in fact the rotor of the USM motor, the part that rotates. (In actuality, these are two separate rings, fastened together.) We note that when the motor is not energized, its rotor is essentially braked by friction between the stator and the rotor, under the influence of the spring (pressure between the two is needed to make the motor work anyway), so we need no further friction arrangement to eliminate "reaction" movement of the rotor when we move the other input ring during manual focusing.

The lower input ring is driven by the manual focus ring.

Here, we do need a frictional brake on that input ring, which is provided by the fixed pressure/drag plate against which it rides axially.

We see that the spring does three things:

- Holds the USM motor rotor against the stator, required for the motor to operate, and as well to provide "braking" of the rotor when the motor is not being driven.

- Holds the two input rings tightly against the three output wheels, so the differential drive action will take place as we previously described.

- Holds the lower input ring against the pressure plate to provide the frictional drag just mentioned.

As mentioned above, the output ring drives the focus cam barrel by way of a key that accommodates slight differences in the "orbits" of the two members so that no binding will occur.

Note that if we turn the manual focusing ring until the focus cam barrel reaches the end of its travel, forced further movement of the ring will cause the output wheels to "skid" against the input ring, accommodating the overtravel. Thus no separate relief clutch is needed.

In the implementation of this type of differential in typical Canon EF-series lenses with mechanical FTM, an important detail is slightly different. It is illustrated in figure 9.

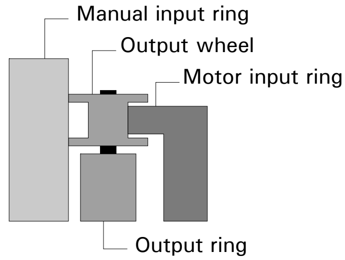

Figure 9. Unequal-ratio differential

We see the rings in cross section. The rotary axis (also the lens axis) is horizontal, well below the figure. We show the output wheel outboard of the ring, rather than hanging in a window, as in earlier conceptual drawings—this is the actual arrangement in the Canon systems.

Note that here the differential wheels have a reduced diameter portion, and the motor input ring (driven by the USM rotor) has a lip at its edge that rides on that reduced diameter. The result is that the “scaling constants” governing the differential operation are no longer equal. We can visualize the lever of figure 5 with the distances **x-y** and **y-z** no longer equal.

Thus, for a given rotation of the USM rotor (one input to the differential), the output ring moves greater than half that amount; for a given rotation of the manual input, the output ring moves less than half that amount. Accordingly, the motor drive can more quickly move the focus cam barrel, while the operation of the manual focusing ring is “more refined”.

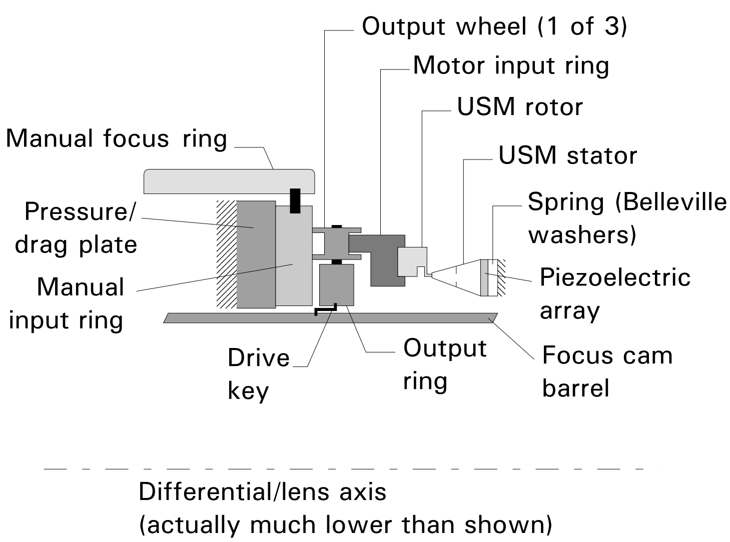

Figure 10. EF lens—ring USM drive with mechanical FTM

In figure 10, we see all this put together in a hypothetical EF lens with ring USM drive and mechanical FTM.

The manual focus input ring is driven from the manual focus ring via a coupling pin, which passes through a continuous slot between two parts of the outer lens barrel. The USM rotor is directly connected to the motor input ring. The output ring drives the focus cam barrel via a drive key. This allows for slight disagreement between the “orbits” of the ring and the barrel, avoiding any binding.

Of course the actual details vary somewhat over the different lenses in which this arrangement is used.

THE MICRO USM DRIVE

Introduction

While the ring USM drive is a very desirable mechanism, it was not ideal for application across the entire EF lens line. For one thing, tooling for this mechanism is very costly, and it would not be attractive to manufacture it in numerous diameters to accommodate the dimensions of various lenses.

Accordingly, Canon developed another exploitation of the ultrasonic drive principle, the ring USM drive. Here, the motor is a small cylinder, suitable for deployment in the annulus between the lens optical barrel and the lens outer barrel. It drives the focus cam barrel through a simple gear train. The principle is quite different from that of the ring USM motor.

Principle

In figure 11 we can see the general arrangement of the micro USM motor and the principle of its operation.

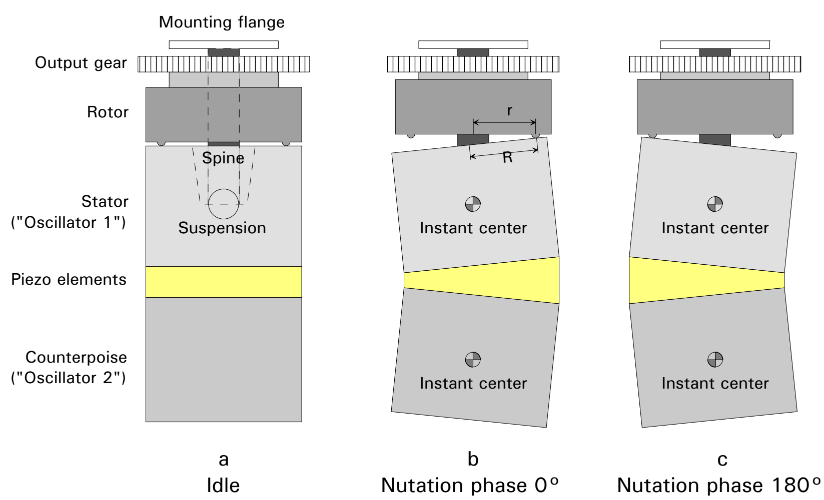

Figure 11. Principle of the micro USM motor

As before, the drawing is stylized for clarity (and to ease the labor of the illustrator—*moi*), and thus the exact shapes and proportions of the components of the actual motors differ from what is intimated in the figure.

In panel **a**, we see the motor deenergized. We see the stator (also called by Canon “oscillator 1”) sitting on a pad of piezoelectric elements that in turn sits on a “counterpoise” (my term), which Canon calls “oscillator 2” (you’ll see shortly that these terms are apt). This package is suspended from a “spine”, at the top end of which is the flange used to mount the motor in the surrounding mechanism (often a “gearbox” assembly). The inside of the stator is hollow to accommodate (and clear) the spine.

There is what amounts to a swivel connection between the spine and the stator at the point of “suspension”. The stator is keyed to the spine so it cannot rotate.

The output gear and rotor both run on bearings on the spine, but the rotor can slide along the spine. The rotor is keyed to the hub of the gear so that as the rotor turns, so will the gear. A spring (not shown) presses the rotor down into contact with the stator.

In the piezoelectric array, there are two active layers, each divided into semicircular halves. The halves in one layer are at right angles to the halves in the other. An AC signal is applied to each layer, in such a way that at one polarity the layer gets thicker on one edge and thinner on the opposite edge (by a very tiny amount). The excitations to the two layers are 90° out of time phase. Thus, in effect, we have a thickening toward the edge that runs around the piezoelectric array, once per cycle of the excitation. I do not know the frequency, but it is likely in the area of 30,000 Hz. Thus, this “thickening” runs around the array perhaps 30,000 times per second.

In panels **b** and **c**, we see the effect of this at two different instants in time, a half cycle apart. The moving bulge makes the stator move in the way a person would move his head in trying to exercise a stiff neck (while continuing to look forward). The rotor does not rotate, but its axis (now at a slight angle to the axis of the whole motor) does rotate about the motor axis, a movement formally known as *nutation*.[4]

In panel **b**, we see the rotor tipped to our left. Next, 1/4 cycle later, it might be tipped away from us (not illustrated). Next (as seen in panel **c**) it is tipped to our right. Finally, it would be tipped toward us (also not illustrated).

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[4] It is sometimes, but inaccurately, spoken of as *precession*. Precession refers to a similar motion of the axis of a rotating body; the stator is not a rotating body.

Its movement is centered on an "instant center" that is nearly at the point of suspension, not so much because that is a "hard joint" but rather because the motion is essentially inclined to be about the center of gravity of the rotor, which the designers have collocated with the point of suspension, and which becomes the instant center.

As this happens, the reaction force at the bottom of the piezoelectric array causes the counterpoise to undergo a mirror-image movement. This occurs about its own instant center, essentially its center of gravity.

Note that this takes the place of having to have the bottom of the piezoelectric layer on some "immovable" base that would anchor the reaction forces. (The forces here are substantial, and so an "immovable" base is hard to arrange in a miniature apparatus.) [5]

Because of the symmetry, this result is no net inertial "reaction" against the entire motor, either in a side-to-side way or in an angular ("swaying") way. Thus there is no radial force on the spine, which does not have to work very hard to keep the stator in place.

I have shown the rotor as having a raised rib on its lower surface that contacts the top of the rotor. Note that the distance from the center of the rotor face to the point of contact, *R*, is greater than the distance from the center of the rotor to the point of contact, *r*. Since there is constant rolling contact between the rib of the stator and the "contact track" of the rotor, the circumferential distance traversed by the point of contact over any time interval must be the same for both.[6]

For one cycle of nutation, the point of contact moves $2\pi R$ units along the stator "track". But the circumference of the contact rib on the rotor is $2\pi r$, a smaller distance. So when the contact point has moved a distance of $2\pi R$ units along that rib (because of the action of the stator over one cycle of nutation), the rotor has had to rotate a little to make up the shortfall on its end.

It is in fact this which causes the rotor to rotate. The rotation is in the direction opposite to the direction of nutation.

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[5] This is the same concept as when we drive a long wire or tall mast radio antenna with a voltage from the transmitter which does not "return to ground" (perhaps there is no good ground readily obtainable at the site) but instead returns to an array of wires radiating from the base of the antenna—a counterpoise.

[6] In the actual implementation, this "rib" is on a separate hardened rim, much like the lip on the ring USM rotor.

The actual amount by which the rim of the stator is raised at its high point is very small, perhaps only 0.002 mm. Thus the difference between $2\pi R$ and $2\pi r$ is very small, and the rotation of the rotor (for each cycle of nutation of the stator) is very small. Thus, even for the very rapid nutation rate, the actual angular speed of the motor output is modest (and the available torque is quite substantial).

Accordingly, we can couple the motor output via a simple idler gear system to the focus cam barrel, no high-ratio multi-stage gear reduction being required.

The mounting of the whole motor by its "nose" is advantageous for a number of reasons, notably that it allows best control of the engagement of the output gear with the gear it drives with the appropriate very small clearance.

Full time manual focus—not

Most lenses with micro USM drive do not have the full time manual focus (FTM) feature. On those lenses, the MF/AF selector, in the MF position, not only tells the system that it is in the manual focus mode, but also slides a gear in the route from the motor to the focus cam barrel out of engagement to get the motor out of the picture. In fact, in such micro USM lenses, it is futile to try to move the focus cam with the motor still engaged—with the motor deenergized, it would take a great deal of torque to turn the rotor, which is pressed onto the face of the stator by the spring.

In order to prevent damage from trying to turn the manual focusing ring with the focus cam barrel at an end of its travel, there is always some form of slip clutch between the manual ring and the cam barrel. If the motor is left engaged (the selector at "AF"), this also comes into play to prevent mayhem from improvident attempts to manually focus.

THE EF 50 mm f1.4 USM LENS

Full time manual focus—yes

The Canon EF 50mm f/1.4 lens (introduced in 1997) was envisioned as being very attractive to photographers. That focal length, for 35-mm full-frame film cameras, and for digital cameras with that format size, is in a sense the "normal" lens. On cameras with a sensor 62.5% of that size (in linear dimensions), such as many Canon digital SLR cameras (the so-called "1.6x" cameras), it provides the same field of view as would an 80 mm lens on a full-frame 35-mm format, very attractive for many uses (including portraiture).

Canon did not see this design as appropriate for the ring USM drive, but recognized that serious photographers would want full time manual focusing for many tasks. Thus they designed a special FTM scheme, compatible with the micro USM motor, for use on that lens.

It has a number of shortcomings, and was not used again in any further lens designs. But it is still the current mechanism for the EF 50 mm f/1.4 lens—there is no “version II”.

Although Canon provides quite complete descriptions of the principle and actual configuration of the ring USM motor itself, the micro USM motor itself, and the differential used with the ring USM motor to implement FTM, they do not choose to give us much information about the special FTM mechanism on the EF 50 mm f/1.4 USM lens. In their book, *EF Lens Work III*, they say only that there is a differential built into the gear unit. Canon’s technical information office, evidently from some official document, speaks of a “ball-bearing mechanism” in the path of the movements, with no further insight into what that means.

Interested users have, over the years, conjectured that the mechanism involves either:

- A differential, functionally equivalent to that in the ring USM mechanical FTM system (although obviously quite different in physical construction and probably in principle), or

- A clutch mechanism, in which when the user begins to turn the manual focus ring, its preliminary movement causes the ring to be coupled to the focus cam barrel and the motor to be decoupled from the focus cam barrel.

Credence has been lent to the latter conjecture by the fact that these lenses, in general, exhibit a substantial amount of “lost motion” of the manual focusing ring before the focus cam barrel begins to move, as would be required to “shift” the clutch system.

Accordingly, we here at ***laboratories dak*** have “borrowed” a complete AF drive assembly (motor, gearing, etc) for the EF 50 mm f/1.4 USM lens, and have “reverse engineered” it. The following discussion is largely based on the results of that exercise.

The EF 50 mm f/1.4 USM lens FTM mechanism

In fact, the FTM functionality of the EF 50 mm f/1.4 USM lens is based on a differential, functionally equivalent to the differential in the ring USM lenses with mechanical FTM, but indeed quite different in its detailed arrangement and in how it is insinuated into the AF drive chain.

In figure 12 we see an overview of the mechanism, with some key components called out.

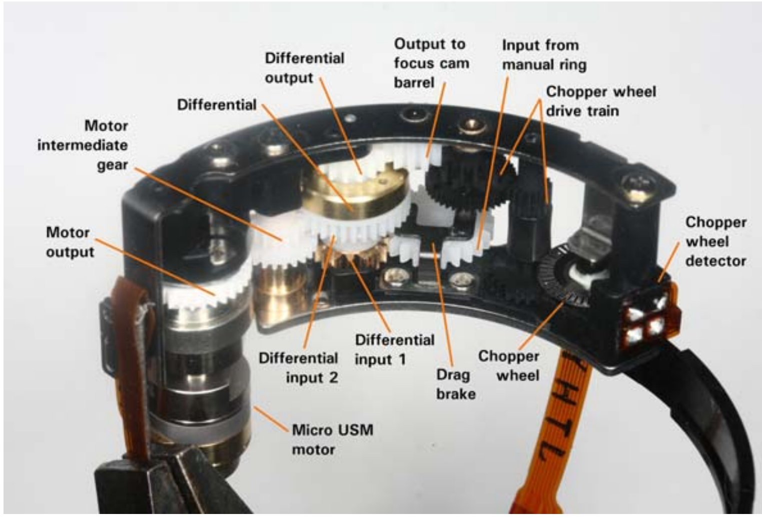

Figure 12. EF 50mm f/1.4 USM drive assembly

The brass-colored "drum" contains a differential mechanism (we'll discuss it in a little while). The brass-colored gear at the bottom of the "stack" is one input to the differential, and is driven by the manual focus ring through an idler gear. The gear just below the drum, which is actually fastened to the drum, is the other input. It is driven by the micro USM motor through an intermediate gear. The gear at the top of the stack (protruding from the drum) is the output of the differential. It drives the focus cam barrel through an idler gear.

We also see in the picture a chopper wheel and associated detector. This produces a pulse for each certain increment of focus cam barrel rotation. The instruction given to the lens to move the focus position, by the autofocus system in the camera body, is in terms of "ticks" (half pulse cycles) of this wheel.

Very roughly (I didn't have the patience to count it exactly), it produces on the order of 30 ticks per tooth of movement of the output gear.

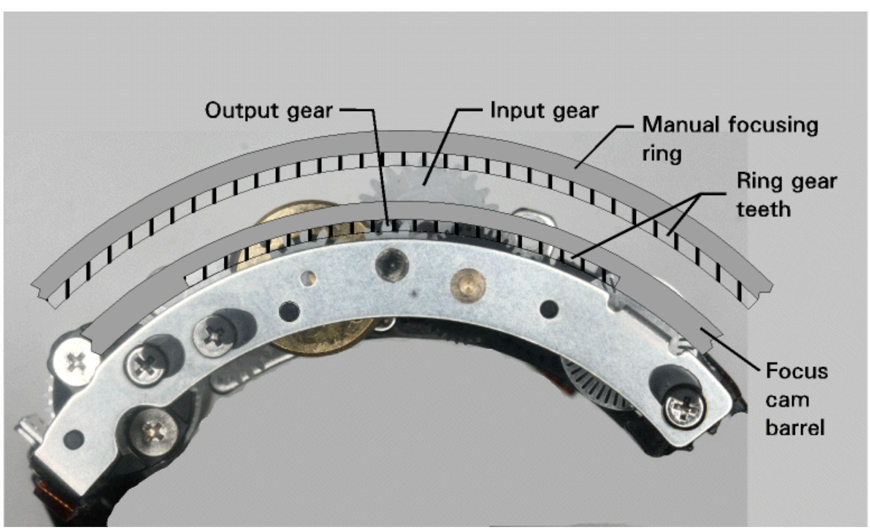

Figure 13. Interface with manual focusing ring and focus cam barrel

In figure 13, we see how the drive mechanism interfaces with the manual focusing ring and the focus cam barrel.

The output gear of the mechanism drives the focusing cam barrel through a ring gear sector. Its angular scope only has to be enough to accommodate the range of rotation of the barrel. It is a separate brass piece, let into a slot in the barrel itself.

The input gear projects through a slot in the focus cam barrel (not illustrated), and engages ring gear teeth on the inside of the manual focusing ring. They run all around the ring, as it can potentially be turned continuously.

We are not certain of the exact arrangement of the differential itself (the mechanism is only "borrowed" and we are not at liberty to dissect it). It is likely of the so-called "ball bearing" type. Figure 14 shows that principle.

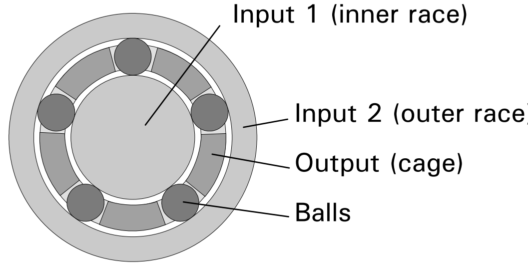

Figure 14. "Ball bearing" differential

Input 1 turns the inner race; input 2 turns the outer race. The ball cage is the output.

This type of differential inherently has different ratios between the two inputs and the output. The sum of the two ratios (expressed in angular terms) must equal 1.0. The ratio for input 1 (as labeled in the figure) is always the smaller one, and thus always less than 0.5. If the contact radius of the inner race is r, and that of the outer race is R, then the ratio for input 1, k_1 (on an angular basis) is:

$$k_1 = \frac{r}{r+R} \qquad (1)$$

and the ratio for input 2, k_2, is:

$$k_1 = \frac{R}{r+R} \qquad (2)$$

In the specific unit under discussion, in terms of tooth count, from the manual ring input to the output to the focusing cam barrel, the ratio is about 0.25 (output at 1/4 the rate of the input).

As we noted before, in a differential-based system, when we do not intend to turn one of the inputs, it must be braked. Otherwise, assuming there is a load on the output, when the other input is turned, the idle input will turn (by virtue of reaction torque) rather than the output.

In this drive, the motor input is inherently braked when the motor is not energized (the rotor and stator are held together by spring pressure). Braking for the manual ring input is provided by a two-pronged friction brake (seen in figure 12).

The infamous "lost motion"

A bothersome idiosyncrasy of the EF 50mm 1.4 lens is that it typically exhibits a substantial amount of "lost motion" in the manual focusing ring operation. If the ring has been turned in one direction, and then we reverse its direction (to "zero in" on the best focus), the ring turns a substantial amount before the focusing cam barrel (and the distance scale, which is on it) begin to move. In my personal copy of the lens, that lost motion is about 4.5° of rotation of the manual ring. This behavior makes precise manual focusing very difficult.

There has been much conjecture as to the source of this lost motion. Some observers have thought that this motion is required in order to shift the clutch mechanism conjectured to be involved in manual focus operation with this lens. Of course, there is no clutch mechanism.

It now seems as if this lost motion is just the result of the accumulation of lost motion at multiple points in various paths in the focus drive mechanism, namely:

- In the path from the manual ring to differential input 1.
- In the path from the motor rotor to differential input 2.
- In the differential itself (such as play between the balls and the cage).
- In the path from the differential output to the focus cam barrel.

One might ask why play in the path from the motor rotor to differential input 2 would be in this picture. Recall that we depend on that differential input being held fixed while the manual ring is being turned. We rely on the self-braking characteristic of the motor rotor for this.

However, if there is any lost motion between the motor rotor and differential input 2, then when the manual ring is first moved in a contrary direction, differential input 2 is able to turn until that lost motion is taken up. Until that happens, there is not enough torque at the differential output to move the focus cam barrel. Thus, that lost motion adds into the overall equation of lost motion as observed at the input gear.

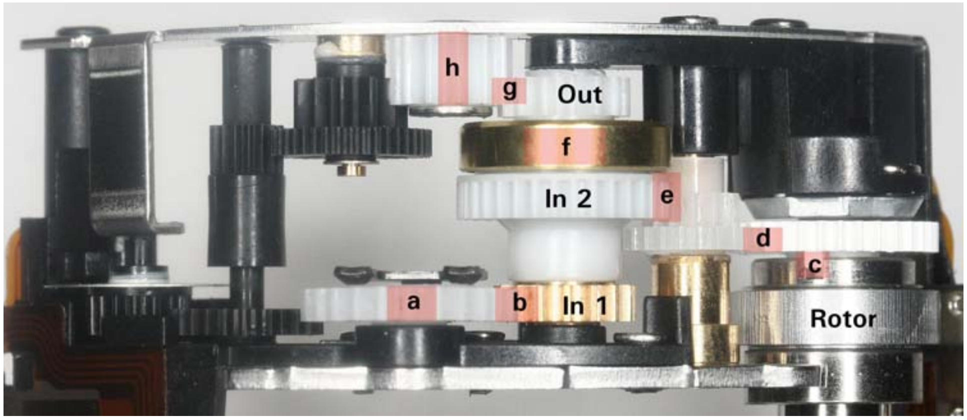

Figure 15. Sites of lost motion

In figure 15, we see the drive mechanism with these lost motion sites identified by shaded areas (pink, if you're seeing this in color).

Site **a** is the contact between the ring gear on the manual focusing ring (not seen here) and this gear in the mechanism. Site **b** is the contact between this gear and the ring gear sector on the focus cam barrel (not seen here). We cannot determine the amount of lost motion at those sites from the mechanism out of the lens—it would have to be evaluated on a partially-dissembled lens.

Site **c** is a keyed slip joint between the motor rotor and the motor output gear (needed to allow the rotor freedom to be pressed down by a spring into contact with the stator). The lost motion here is very small but perceptible.

Site **f** represents lost motion in the differential itself, from whatever cause. In the specimen unit, this was negligible.

Overall, in the specimen unit, the overall lost motion, as seen at the input gear (**a**), with the output gear (**h**) fixed, is about 1.5 teeth of the input gear. This almost corresponds to the overall lost motion observed in our copy of the lens. Most of this is contributed by the various sites of gear-to-gear contact.

We suspect that the lost motion at site **h** (with the ring gear sector on the focus cam barrel) is a significant contributor to the total. Because of the differential ratio, on a "tooth count" basis, lost motion of (for example) 0.1 tooth pitch at site **h** would lead to a lost motion of approximately 0.4 tooth pitch at the manual ring input (site **a**).

Some of our correspondents have reported that on their copies of this lens the lost motion is greatest with the focus near one end of its range, and less in mid range (essentially none in the case of one report).

We suspect that this is a result of the focus cam barrel ring gear sector (a separate piece "let into" a slot in the barrel itself) may be deformed from its ideal circular form—in particular, bowed in at its center. The result may be a decrease in the clearance, and thus the lost motion, at mid range. We have no confirmation of this conjecture.

The infamous "susceptibility to damage"

The EF 50mm f/1.4 USM lens is also infamous for supposedly being highly susceptible to damage to the focusing mechanism. It seems that most of this reputation comes from a situation I will describe in this section.

First we note that the optical principle used for focusing in this lens is what is described as *all-group linear extension*. This simply means that all lens elements are mounted, at fixed spacing, in a housing I will call the *optical barrel*. This barrel is moved along the lens axis to change the focus, just as the lens in a view camera is moved. (This is as distinguished from the focusing systems found in most EF-series lenses, in which one group of elements—perhaps the frontmost, or the rearmost, or one in between—is moved to change the focus. Some times, in lenses said to have the *floating system*, two groups of lenses are moved by separate amounts.)

In the EF 50 mm f/1.4 USM lens, when focused at the closest distance, the optical barrel projects quite a distance out the front of the lens external housing. When focused at infinity, the optical barrel still projects beyond the housing, by about 2 mm.

As a result, if the front of the lens should strike, for example, a door frame, as the photographer moves about, it is very likely that the front of the optical barrel will take the hit, being driven back into the lens.

The optical barrel has, at its rear, off to one side, a relatively deep rectangular "bore". This rides on a rectangular cross-section prong ("key") projecting forward from the rear of the lens. This keeps the optical barrel centered, prevents it from rotating, and keeps it traveling along an axial path.

The focus cam barrel has projecting from it three small nylon shoes, which travel in circular slots in a surrounding barrel—this is how the focus cam barrel is suspended. It does not shift along the lens axis.

The optical barrel has projecting from it two similar shoes, which travel in helical slots in the focusing cam barrel. Thus, as the focusing cam barrel rotates, under the influence of the drive mechanism described in detail above, the optical barrel is moved fore or aft as needed.

Here we encounter an unfortunate design detail. In figure 16 we see the focus cam barrel and one of those helical slots, with the focus set to almost infinity. Note how thin is the bridge of metal connecting one side of the groove to the rest of the focus cam barrel.

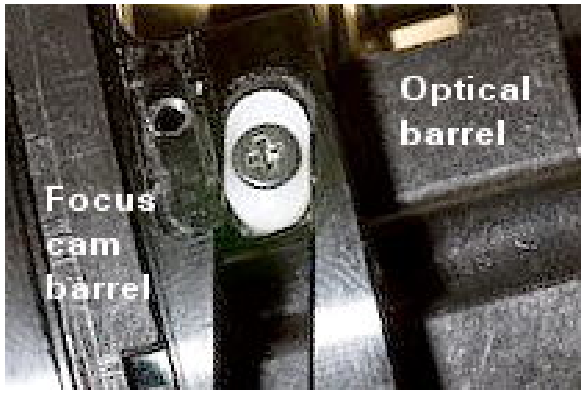

Figure 16. Helical slot

Photo by "Nick Canada"

You can imagine that if the optical barrel strikes an obstacle, and so is driven in the rearward direction (to the right on the figure), that thin bridge will take a great deal of strain. The typical result of a modest incident is shown in figure 17 (this is the other slot of the same lens).

Figure 17. Helical slot—distorted

Photo by "Nick Canada"

In more severe cases, the bridge is entirely fractured.

Even with the deformation seen here, the behavior of the focusing system is severely compromised (the optical barrel can "cock" on its guiding key owing to the asymmetry of its propulsion at the two shoes). Often, the AF drive system is unable to start the optical barrel moving from its infinity position.

(Our own personal copy of this lens suffered what seems to be this same ailment, and I was never aware of any "incident"—the lens has hardly ever been used.)

ACKNOWLEDGMENTS

Thanks to my wife Carla, the Cherokee Red Pencil, for her precise copy editing of this difficult manuscript.

Thanks also to the various members of online forums (prominently Digital Photography Review, ProPhoto Home, and Open Photography Forum) who responded to my survey regarding the prevalence of the "lost motion" phenomenon in the Canon EF 50 mm f/1.4 USM lens.

#

APPENDIX A

Ring USM Piezoelectric Drive

Here we will see in detail how the traveling flexural wave on the stator is generated in a ring USM motor by the piezoelectric array.

In figure 18 we see the layout of the piezoelectric array.

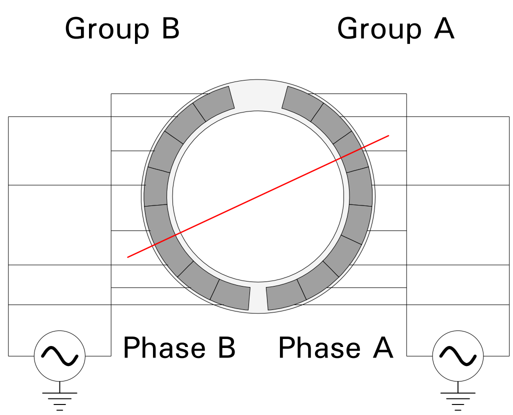

Figure 18. Ring USM piezoelectric array

The ring is shown lightly shaded. The darker shaded areas represent individual piezoelectric “pads” (elements), which are divided into group A and group B. Alternating elements in a group are connected to opposite sides of a balanced AC voltage source, one for each group (the sources being identified as phase A and phase B—the significance of that will be described shortly).

Note that the phase of the angular pattern among the elements of group A is not followed by the elements of group B. Their pattern is shifted by half an element pitch from the pattern for group A—a critical consideration.[7] (The red construction line helps us to see that.)

When one of the elements receives a positive voltage, it bows upward in its center; for a negative voltage, it bows downward at its center. (The elements lie on a resilient substrate to accommodate the resulting undulation of the set of elements.)

We continue on figure 19. In panel **a** we see the elements of group A energized by the Phase A source (assuming for the moment that the group B elements are not energized). We see them at a peak in the output of the phase A source with the polarity shown.

[7] The corresponding illustration used by Canon—for example, in their book *EF Lens Work III*—does not show this offset. As a result, readers following the description of operation there cannot see how the thing can work.

Accordingly, the elements shown in lighter gray are bowed upward and the ones in darker gray are bowed downward. The frequency of the excitation corresponds to the resonant frequency of the ring in one of its flexural modes. Thus the ring gladly follows the impetus given by the group A elements and (at this instant of time) has risen slightly at the points shown with open circles and fallen slightly at the points shown with black circles (see panel **a**).

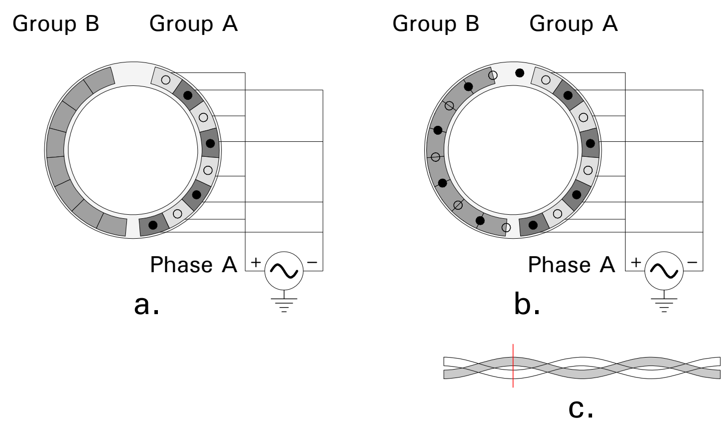

Figure 19. Group A elements energized

But in fact because of the resonance of the ring, and coupling within it, the ring actually flexes as shown in panel **b**, at this instant having risen slightly at **all** the points shown with open circles and fallen slightly at **all** the points shown with black circles.

Note that this is not a wave that travels around the ring—it is a *standing wave*. As the excitation changes its instantaneous polarity, the ring rises and falls at the “open circle” points, and falls and rises at the “black circle” points. At the places halfway between, there is a null: the ring neither rises or falls there (but flexes).

In panel **c** we see a portion of the ring from the side. The shaded image shows the ring at one peak of the flexural excursion, and the unshaded image shows it one-half cycle of the excitation later.

In figure 20 we disconnect the phase A excitation from the group A elements, and instead connect the phase b excitation to the group B elements.

The story is exactly the same as before: a standing wave extending around the ring is created. Here, at the instant of interest, the raised and lowered points on the ring are shown by boxes rather than circles (to remind us that they are different from the points seen on figure 19). In panel **c** we see the standing wave created in this case for the same portion of the ring seen in figure 19 (the red reference line corresponds to the same point on the ring in both figures). Note however that this standing wave is aligned 1/4 pitch away from the alignment of the standing wave seen in figure 19 (a natural result of the different alignment of the group B elements).

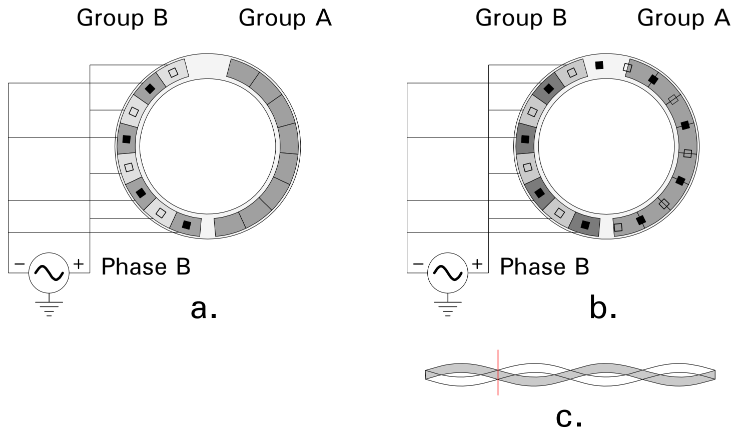

Figure 20. Group B elements energized

In figure 21, we have both sources of excitation connected. The electrical waveform from the phase B source is one quarter cycle (90°) different in phase from the phase A source. We don't show instantaneous polarities at some arbitrary instant in this case.

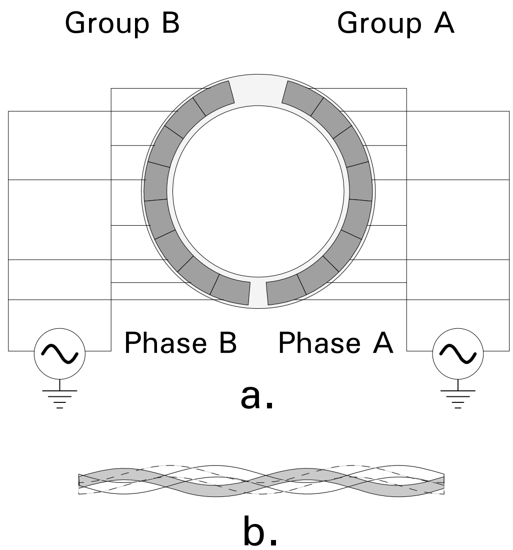

Figure 21. All elements energized

In effect, here both of the standing waves seen individually in figures 19 and 20 coexist. They are physically displaced around the ring by 1/4 of the pitch of the wave, and they are displaced in time by 1/4 the period of the excitation.

The result of the superposition of these two would-be standing waves is a *traveling wave*, which progresses continuously around the ring. In panel **b** we see three snapshots of this at subsequent periods of time. The shaded image represents the ring at one instant. The unshaded image with a dotted boundary represents it 1/4 of the excitation period later; the unshaded image with a solid border represents the ring 1/4 period later yet. We can see that the wave is traveling to the right.

Thus the pattern of undulation in the ring (the wave), which repeats all around the ring at any instant, travels around the ring. It will travel a full revolution in 9 excitation periods. Thus, if the excitation is at a frequency of 27,000 Hz, the wave will travel around the ring 3000 times per second.

Note that if we reverse the polarity of one of the excitation sources, the wave will propagate around the ring in the opposite direction.

It is of course this traveling pattern of undulation of the ring that, by virtue of the paths of the tooth tips, causes the motion of the rotor, as described in the body of the article.

Maintaining resonance

Attaining the desired amplitude of undulation depends on the excitation frequency precisely matching the natural resonance of the stator in the vibration mode of interest[8]. That will of course vary from unit to unit owing to small variations in dimensions, and in a given unit will vary with environmental conditions (notably the temperature of the stator).

To assure that the system is always excited at the current resonant frequency of the stator, a feedback control system is used. A separate piezoelectric pad (not seen in figure 18) is not electrically excited, but rather serves as a “pickup” (they are reciprocal—can act as either “motor” or “generator”). Its electrical output reflects the instantaneous undulation of the stator at its location. The phase of that signal will either lead or lag its ideal phase with respect to the excitation if the excitation is either above or below the resonant frequency of the stator.

Any such discrepancy is noted and used to cause a gradual change in the frequency of the excitation until proper resonance is indicated.

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[8] *Mode* here refers to how many cycles of the wave there are around the entire ring. This depends on the physical properties of the ring and the frequency of the excitation. For each mode, there is a precise frequency that maximizes the response.