Two-Axis Sawyer Motor for Motion Systems

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ABSTRACT: For a number of years, two-axis Sawyer motors have been used as motive devices for flatbed plotters and wafer probers. These two applications are quite different in their requirements for motor dynamics, but both depend on the motor's high speed and good open-loop positioning capability, as well as on its almost unlimited life expectancy. The motors are now being applied to a variety of other motion system requirements, and motor and control drive electronics tailored to these more general applications are being produced. This paper presents some general properties of the motors and describes the control strategies utilized to maximize their performance.

Introduction

It is best to begin a discussion of Sawyer motors with an overview of the operating principles. The subject is covered in some detail in other published papers [1]–[3], which cover the operating principles of the motor and the control dynamics of the single-axis version.

Figure 1 is a simplified drawing of the pole structure of a two-phase Sawyer motor. The motor consists of two parts. The forcer contains the permanent magnet and the driving coils and is, in most systems, the moving part. The platen is a passive magnetic structure that supplies the return path of the magnetic field of the forcer. The platen is long enough to accommodate the desired length of motion. The motor operates by using NI action of the coil to commutate the permanent magnetic flux of the forcer. For various values of I_1 and I_2, there is a stable equilibrium position for which the forcer will generate displacement force when the motor is moved away from the stable position. The simplest relationship that can be used in the motor is the sine relation, where X is the position of the forcer along the platen and P is the pole pitch, generally 0.040 in.

$$I_1 = I_A \sin(2\pi X/P), \; I_2 = I_A \cos(2\pi X/P) \tag{1}$$

While Eq. (1) defines a unique position for the current for each equilibrium position, the inverse relation is not unique. For any pair of currents I_1 and I_2, there is a family of equilibrium points spaced by P along the platen. The motor can reside in any of these positions.

If the motor is initially established at a stable point, it can be moved along the platen by varying I in accordance with Eq. (1), but if the motor is pulled from the desired position for any reason, it can come to rest at any tooth position defined by the equation. The most common way that the motor can lose position is to be commanded to move at an acceleration that requires that it generate more force than the motor can supply. When this happens, the motor will cease to follow its commanded position and all reference to the desired position will be lost. To gain the maximum performance from the motor, it is necessary to drive it with a control system that consistently utilizes a safe percentage of the motor's available force, and no more.

Starting from this background, we can now see how two single-axis motors can be combined in a single frame to produce a motor capable of moving in two coordinates simultaneously. In order to provide for simultaneous motion in two axes, the platen must be cut in two axes rather than into the bars that characterize the single-axis platens. The resultant platen looks like a series of rectangular plateaus, each one-half the pole pitch dimension, and each surrounded by a series of valleys also one-half a pole pitch dimension.

As can be seen in Fig. 2, the resulting array looks somewhat like a waffle, and is generally referred to as a waffle platen. The pole dimensions on the platen are subject to variation, and there are a variety of possible dimension sets that could be used. On one hand, using a large pole pitch makes the motors easier to build and the individual tolerances required somewhat larger. This results in a motor that is not as stiff as far as its force characteristics are concerned. On the other hand, making the pole pitch smaller makes the motors physically more sensitive to dimensional errors, but produces a stiffer motor. In a smaller motor, the period of the cyclic errors is reduced, and, hence, the amplitude is also reduced. As a matter of practice, motors are manufactured with pole pitches of both 20 mils and 40 mils. For the purposes of this paper, all examples will be based on a motor of 40-mil platen pitch.

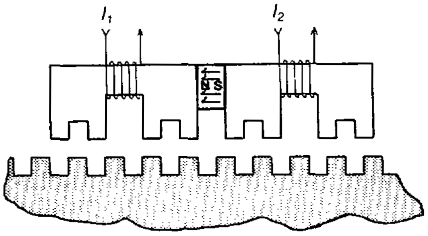

Fig. 1. Simplified pole structure for a Sawyer motor.

The structure called *the platen*—while passive (containing no current-carrying conductors)—has at least as much effect on the performance of the system as the motors do, and, if anything, is more difficult to manufacture. The positional accuracy of a system is determined almost entirely by the accuracy of the platen. Unlike the motors, however, the accuracy must be maintained over the entire movement field of the positioning system.

Motor Dynamics

If a motor were actually constructed like Fig. 1, it would have some serious dynamic

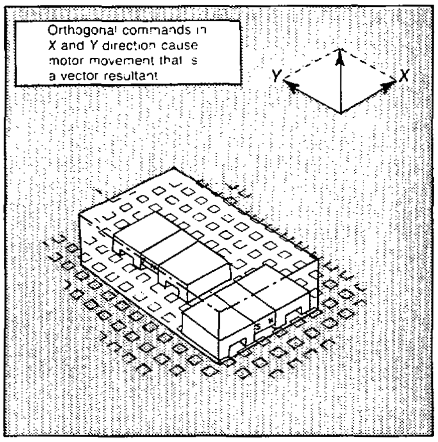

Fig. 2. Two-axis motor and platen.

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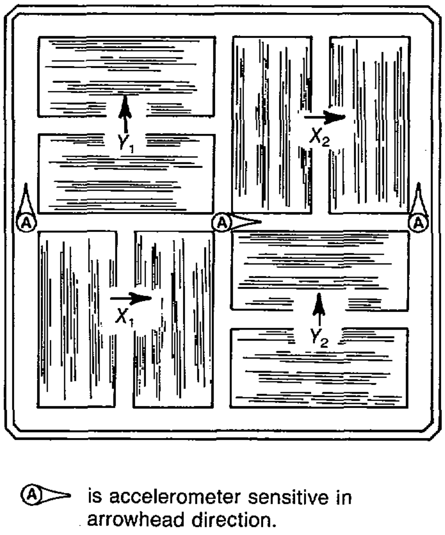

Fig. 3. Typical two-axis forcer layout.

problems. The force vector for only one forcer could pass through the center of mass of the motor. The other asymmetrically disposed forcer would produce force to both translate and rotate the motor. This rotation would produce some very undesirable side effects.

In order to provide a geometry in which all forces are applied through the center of gravity, a forcer layout like Fig. 3 is generally used. In this arrangement, forcers are located on both sides of the center. This provides symmetrical force, but also makes possible another control strategy: the use of an accelerometer servo system to improve the linear dynamics of the motor and counter the tendency to rotate or, more correctly, to be excited into rotational oscillations.

To understand the dynamic problems, we need to look at the force displacement characteristic of Fig. 4. The line AB is the apparent spring constant, which is a characteristic of the motor. On the linear axis, the spring constant combines with the mass of the system to provide a mechanical resonate system with relatively little damping. This creates the underdamped stop characteristic as well as the transient experienced when acceleration is changed. These characteristics are explained in [3] in the case of single-axis motors. In the case of two-axis motors, there is one more degree of freedom.

Looking at Fig. 5, we can see that each forcer is restraining rotation with a force proportional to the amount of rotation. The resultant frequency of oscillation is obtained approximately, where k is the force constant (defined in Fig. 4), I is the moment of inertia about the center of gravity (CG), and r is the radial spacing of the forcer from the CG.

$$f_0 = (r/\pi)(k/I)^{1/2}$$

As an example, for a forcer that has a force constant of 1570 lb/in. and a mass of 10 lb with $r = 1.5$ in. and with a 10-lb mass evenly distributed over a 4-in.^{2} area, the resultant rotational frequency would be about 72 Hz, whereas the linear resonance of such a structure would occur at about 55 Hz. Of greater importance, however, is the fact that the amplitude of motion that can be tolerated in a rotational mode is much less than that which can be tolerated for the translational vibrations.

Displacement of one-eighth of the pole pitch results in only about a 30 percent reduction in the apparent force constant for translational motion, but when the four forcers are rotated relative to the platen, the pole slots are misaligned relative to the platen and the force drops even more rapidly. If the poles are rotated so that they are one-quarter of a full pitch out of registration at the end, almost all of the restoring force of the motor will have been lost. In translation, a motor will be producing its maximum restoring force under such a condition. For rotation of the motor, not only does the operating point move along the curve of Fig. 3 toward point C or D, but points C and D also move toward the X axis. This results in the motors being relatively intolerant of rotational displacement either induced by external forces or by rotational vibration. One of the simplest ways of countering this property is to build motors with large spacings r. This makes the motor more able to resist externally induced rotating forces.

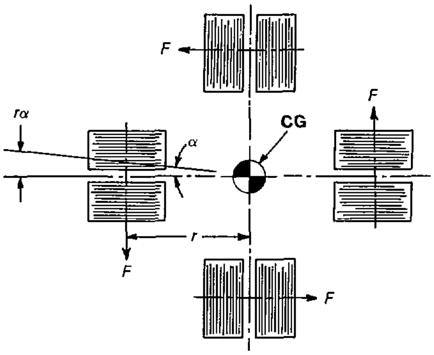

Fig. 5. Equivalent system for rotational dynamics of a Sawyer motor.

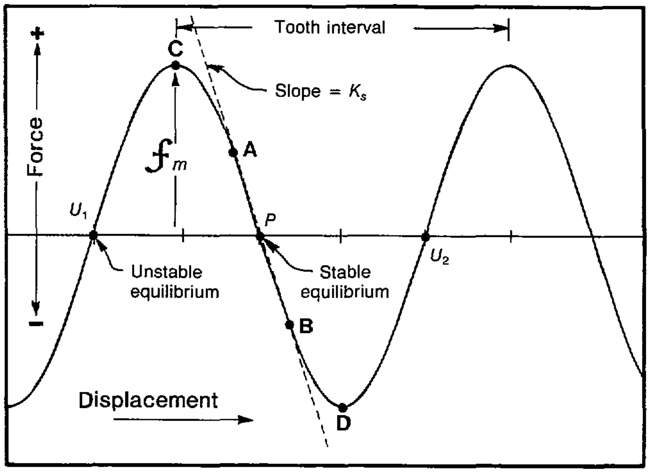

Fig. 4. Motor force versus displacement.

Two Classes of Moves

At this point, we need to define the applications and divide them into two general classes:

(1) The first application areas are those in which the path between two points is important. These applications would include plotters, profile cutters, and contouring devices.

(2) The second general areas of application are those in which the goal is to move from point A to point B, but the path between the two points is not of importance.

Fortunately, we seldom find all the requirements present in the same application. In the class 1, or path-sensitive applications, it is seldom necessary to provide either end point or path control to much better than 0.002–0.005 in. Speed is sometimes a requirement, but vector speeds of higher than 40 in./sec are rare, because, generally, the devices are drawing lines or cutting material, and the mechanism attached to the end effector cannot work much faster than this.

In the second class, path-independent applications, we frequently find accuracy requirements up to the limit of the technology, and, again, any speed that can be produced would be useful.

This distinction in application is important because the construction of motors and control systems for the two classes of systems is, or at least should be, different.

Accelerometer Feedback

In order to control the transient characteristics of the motors for path control applications, the most successful approach has been to mount accelerometers in the motor body and to use the integrated accelerometer signal to provide what would normally be velocity or tachometer feedback in rotary systems. The question always arises as to why use accelerometers rather than direct velocity measurement. The answer is that most of these motors are used in open-loop systems and, without position feedback, there are not a lot of practical velocity measuring devices available. Some development is under way on electronic sensing of velocity through measurement of the current and voltage wave forms to the motor; however, this is not ready for application at this time, and even when it is, it may not be competitive with the accelerometer approach. The characteristics of the accelerometer system have been discussed in [3]. In general, the amount of feedback applied is that which will provide critical damping or slight overdamping for the motor characteristic.

One familiar with the design of feedback systems of this type will recognize that the gain of the feedback loop needs to be changed if the mass of the moving system changes. Fortunately, with low damping ratios, this requirement is not too critical, and satisfactory performance can generally be achieved over a modest range of operating payloads. As noted in [3], the servo system also needs to have an additional input in the form of an acceleration $\ddot{X}$ or $\ddot{Y}$ in order to eliminate the "following" errors.

Once one has added the necessary accelerometers for controlling the dynamics in X and Y, it requires only one additional accelerometer to allow control of the rotation of the motors. Figure 3 indicates the location of three accelerometers in the motor frame. A single accelerometer aligned in the X direction produces the input for the X servo system. Two accelerometers mounted in the Y direction are averaged to provide the input to the Y servo.

The difference between the two Y accelerometers is a measure of the rotation around some axis of the motor perpendicular to the plane of the desired translational motions. This rotational acceleration signal after integration into a rotational velocity signal is applied to a third servo system, which ultimately drives all four of the forcers to counter the rotation of the motor. The characteristics of the rotational servo system are somewhat different from the X and Y system. Since the motor is not intended to rotate, any efforts to reduce the "following" error in rotation are unnecessary. Similarly, there is no penalty for overdamping in rotation, so the gain can be set somewhat higher to accommodate a larger range of rotational inertias. To an even greater extent than occurs in the X and Y system, one should note that force devoted to countering rotation is not available for axial acceleration, thus reducing the overall performance of the system. For this reason, even though the servo may stabilize rotational characteristics of the system, it is desirable to reduce the demand on the system by operating it with the payload center of gravity as close as possible to the center of the applied force.

In the electronic system required to implement the stabilization system shown in Fig. 6, there is only one unusual element. This is the circuit element called a FAM. This device is a unique analog circuit that modulates the phase angle of the drive signal to the motors to produce changes in force. In newer applications of the system, the function is performed in the digital domain, where it is relatively easy to implement. For

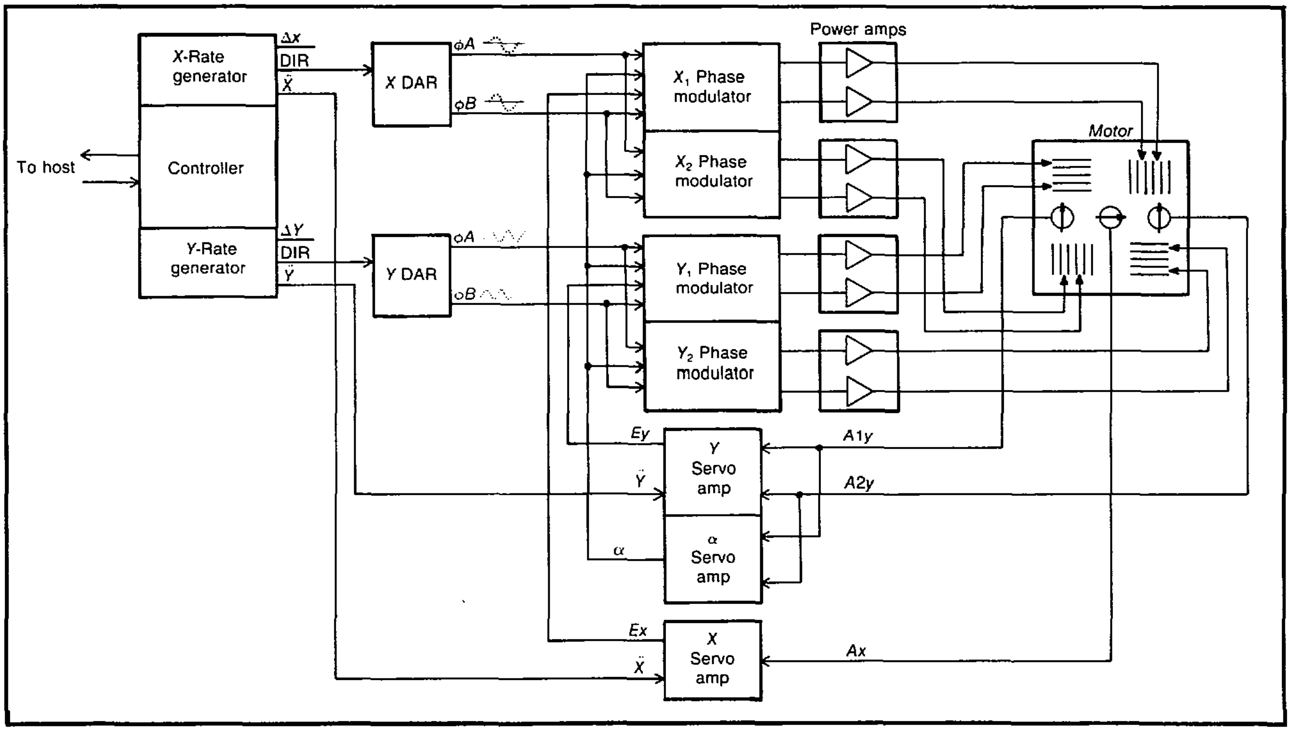

Fig. 6. Block diagram of control system for two-axis motor.

most systems, the phase-angle modulation circuit is implemented with an analog circuit, which approximates the trigonometric identity for the sin and cos of the sum of two angles.

For systems in the path-independent class, there are other approaches open to dealing with the problem of rotational stabilization and even linear dynamics. One of the simplest approaches is to spread the motor out to make it rotationally stiffer, but this is done at the expense of larger and more expensive platens.

End-of-move transients can be shortened by the use of winding source feedback. This is much easier than the design of a continuous damping system, since at the end of a move, the drive signal should be zero and the error signal detected from the windings is more directly accessible.

Accuracy

The basic two-phase forcer described previously has a rather large so-called cyclic error. This is an error that recurs each pole pitch of motion if the phases are driven with sine wave currents. The amplitude of the cyclic error can be as much as 0.002 in., zero to peak. Efforts to compensate for the cyclic error by altering the harmonic content of the driving wave are limited because the errors are not always the same at various points in the platens and, to some extent, depend on the motor's construction. Most of the cyclic errors occur with a period of one-fourth of a tooth pitch, i.e., fourth harmonic pitch.

The fourth harmonic error can be dramatically reduced by combining two forcers displaced one-eighth of a pole pitch from each other and by driving the two forcers with signals 45 deg apart. Motors constructed in this way are referred to as four-phase motors. Not only do these motors have smaller cyclic errors but they are easier to compensate since most of the remaining cyclic error is at a fundamental frequency. Most four-phase motors start with cyclic errors of less than 0.001 in. and can generally be compensated to less than 0.0002 in. The price one pays for four-phase motors is a more complex motor structure and the need for more drive amplifiers. If the motor is of such a rating or size that multiple forcers are required at any rate, there is no penalty associated with the use of four-phase motors.

There is a unique motor arrangement referred to as a hybrid, which uses transformer action in a motor-winding to synthesize the ±45-deg phase signals required for the extra forcers. This arrangement produces the accuracy advantage of a four-phase motor with the drive complexity of a two-phase motor. The hybrid motor does, of course, require more terminal voltage for a given speed than individual winding motors; but, in many cases, the speed is low and the high-voltage drive amplifiers available may lead to no disadvantage in the use of hybrid four-phase motors. With the availability of new switching drive amplifiers with compliance voltages of up to 180 V, the trend toward the use of hybrid four-phase motors is expected to accelerate.

Other major error sources in two-axis Sawyer motors are rotation, hysteresis, and linear dimensional errors in the platen. Rotation is principally due to unbalanced cyclic errors in the opposed forcers and can be reduced by either careful matching of the forcers or by extending the length of the movement arm *r*. Most of the advantage can be gained by extending only one pair, either *X* or *Y*; so it is not uncommon to see motors that have only one long axis.

Hysteresis can, if uncorrected, amount to as much as 0.0003 in. Several strategies have been used to reduce this effect by almost an order of magnitude. One of these techniques uses a rapid high-frequency degaussing oscillation at the end of a move. A simpler reduction method is to arrange moves so that the final part of each move approaches each point from the same side.

Geometrical errors in the platens are properly considered a part of the platen and not of the forcer. These errors are due to the spacing of the lines in the platen not being uniform and, in the case of waffle platens, not perpendicular. Careful manufacturing methods and, hence, high cost are the only known ways to reduce these errors. In the case of the waffle platens, measuring the errors of a platen is a formidable task.

Size of Motors

It appears that no matter what size motors are offered, there is always a need, or at least a desire, for motors of different sizes. For a given material, there is an almost fixed relationship between the motor forcer area and the motor force. Since the motors operate by commutating flux from one pole set to another, the force available is controlled by the flux, which is supported by a pole piece. The flux is established by the properties of the material and by how far one is willing to run the iron into the saturation region. Increasing saturation may allow small increases in force, but at the expense of increased cyclic error and hysteresis losses. With standard iron, the realized figure is about 9 lb/in.^{2} of pole face on a bar platen and about 6 lb/in.^{2} on a waffle platen.

From a cross-section standpoint, almost any motor having the same acceleration or dynamic performance characteristics has the same number of parts and assembly operations; so there is not much reduction in cost associated with shrinking the motor to a smaller size. Because of this, one of the frequently assumed merits of smaller motors seldom materializes; that is, a small motor is not much less costly to make than a large motor.

There are limitations to the preceding. Standard forcers are fabricated with lengths of 1.2 in. giving a force of about 5 lb/forcer, and 2.4 in. giving a force of about 10 lb/forcer. The 2.4-in. forcer is the largest size presently being considered for manufacture. For motors with greater than 10 lb of force, multiple forcer units are required, and motors are generally constructed by using multiples of the large forcer. When one expands above the 10-lb figure, the cost goes up linearly as the number of forcers required.

Speed of Motion

While the motors would appear to have no upper speed limit, there are a few practical limits on what can be achieved. The first limit is established by how much a motor can accelerate in the space available for a move. The motors are generally moving some payload in addition to their own mass, so this places an upper limit on the acceleration possible, and this limit frequently places an upper limit on the speed that can be achieved in a given move regime. As a rule of thumb, most motors are run lightly loaded and accelerations of at least 2 *g* are possible. This means that, for a move of 6 in., the maximum speed that can be achieved would be about 50 in./sec. In practice, the actual speed achieved is less than this because the force of the motor falls off as the speed increases, due to both drive voltage limitations and eddy current losses primarily in the platen. Special controllers oriented toward Sawyer motors have acceleration profiles that match the force-velocity characteristics of the motor and that allow a large percentage of the motor's force to be utilized.

Loss of Registration

First-time users of these motors are frequently concerned with the possibility of a loss of registration. While it is possible to operate motors beyond their capability so that they pull out of registration, this is not nearly as great a problem as one might at first assume. It is not actually too different from other motor systems.

The performance of the motors and their

capabilities are quite well understood, and it is possible to design systems that will not command the motors to do anything of which they are not capable. By providing reasonable safety factors in the motor's command regime, it is possible to design systems that will not pull out of registration unless the motors are accidentally obstructed by some fixed obstacle in their path of motion. Of course, when the systems are powered down, they have no method of maintaining registration, but this is not too different from most other motion-controlled systems. Most *XY* systems depend on rotary motor and drive translators. If they use feedback devices, they generally use incremental encoders, and these also have no reference for their absolute position when power is lost.

There is no question that control of registration should be a matter of concern to system designers, but as a matter of practice, it can easily be dealt with, as has been demonstrated adequately by many years of operations with thousands of these motors in plotter service. In coping with the loss-of-position problem, one must either design a system in which the consequences of the loss of position are acceptable or one must derate the system performance so that the probability of a loss of position is acceptably low. It is a design trade-off that only the system designer familiar with the applications of the system can make intelligently.

Multimotor Systems

One very interesting system that can be constructed involves the use of two or more motors operating on the same platen. As long as the motors do not physically occupy an overlapping space, and as long as the umbilical cords can be kept untangled, workstations disposed over a platen can be served by several motors. The system in Fig. 7 is an example of a typical inspection and rework machine. There might be up to four stations simultaneously in operation. The throughput can then be increased by simultaneously utilizing up to four motors so that all four stations could be utilized full time. The programming to keep the umbilical cords free and untangled and to keep the trajectories clear of the motors is not trivial, but it is also not impossible.

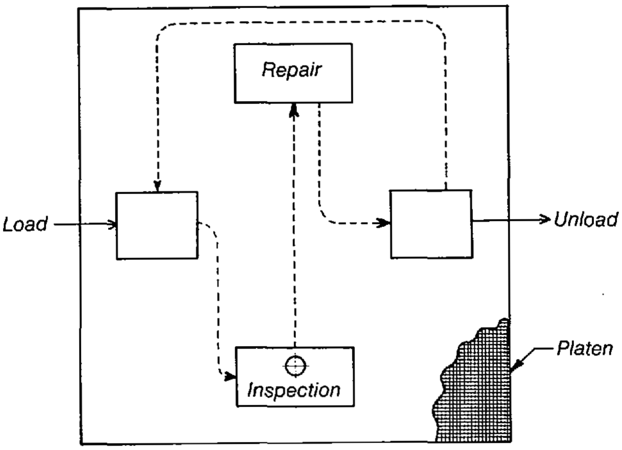

Fig. 7. Layout of two-motor system.

Summary

The two-axis Sawyer motor has been available for a number of years. It has demonstrated an almost perfect record of reliability, but, until recently, the number of different applications served by these motors has not been great. In the present form, the motors are capable of producing open-loop accuracies of close to 0.2 mils if their platens are properly mapped and about 1 mil over small working areas without mapping. Even though most of the discussion has been based on an open-loop positioning system, it should be noted that there are a number of applications in which these motors are being used with laser interferometer feedback. The high-resolution, low-backlash characteristic of these motors fits well with that application.

The parameters of the motor systems with regard to the acceleration and accuracy speed and cost have complex interrelations. Generalizations about these motors are difficult and complex. Nevertheless, the motors are an excellent fit to a variety of applications and should be given consideration anytime a high-reliability, long-life motion system is required.

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