Closing the Loop around a Transverse Flux Hybrid "Step" Motor — The Degrees of "Closed Loop"

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Transverse magnetic flux motors — also known as step motors — become *Hybrid Servos* when you operate them closed loop. This is the same transformation that happens between running a 3-phase synchronous motor from line voltage as opposed to running it closed loop as a brushless servo. In the case of hybrid motors, there are many degrees of what is advertised as "closed loop," and thus significant differences in the performance improvements seen.

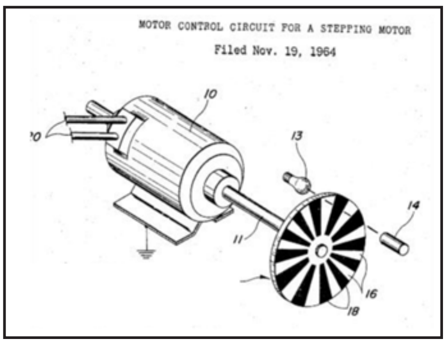

Figure 1 **Early level 1 closed loop step motor using encoder.**

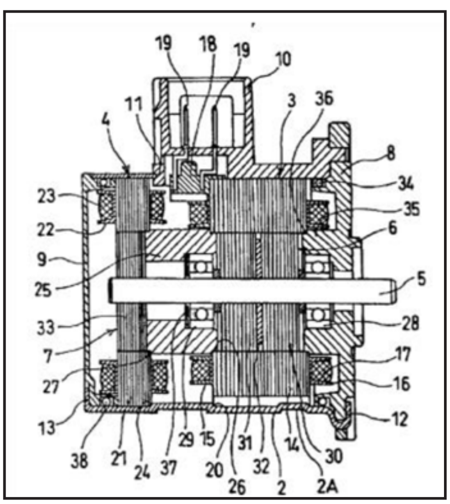

Figure 2 **Step motor including resolver for closed loop.**

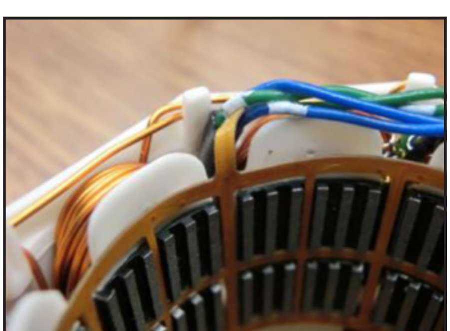

Figure 3 **Mosolver construction.**

Position Feedback Sensors

There are multiple position feedback sensor methods, as well as "sensorless" methods. One of the earlier methods, still popular, is the use of an optical encoder (Patent US3353076 from 1967). The encoder was used to adjust the step position of the motor to "obtain maximum torque without loss of synchronization." The circuitry taught in this patent keeps the motor error from exceeding 1.5 full steps; for full step, maximum torque is obtained by keeping the step angle between .5 and 1.5 step (1 full step average). Patent US4584512 improves on this by providing 64 microsteps to reduce the torque ripple. Newer encoders have higher resolutions to allow a finer position measurement. There are also better control techniques which we will get to later in the article.

Resolvers are absolute position sensors over their sensing interval. A drive signal drives a coil that generates a signal into at least 2 phases of sensor. Figure 2 shows a step motor with a resolver built into the same case (Patent US6849973). The resolver built with the same number of poles allows for easy commutation of the motor. Conventional resolvers require a separate excitation source — usually sinusoidal and a resolver to digital (R/D) converter — used to estimate velocity and position from the received phases. As the excitation passes through zero twice a cycle, the sensor is "blind" at these intervals, so the R/D must estimate what is going on in that time interval; this estimation can cause some phase distortions in the feedback information. Resolvers are not sensitive to most environmental factors, but they typically add size and weight to the motor and require additional electronics to drive and sense the signals.

Patent US7075196 describes the "mosolver" (a contraction of motor and resolver) in which we add a sensor winding into the slightly modified stator of a standard microstep-capable step motor. The motor windings provide the excitation, the existing rotor and stator gate the magnetic field through the coils on the sensing winding to provide sine- and cosine-related signals that are used for feedback as well as for commutation. The measured AC component of these signals comes from the ripple current resulting from the chopper drive. These signals are fed into spare A/D channels on the controller. These show a resolution of 32,000-counts-per- revolution. Additionally, the sampling rate equals the chopping rate of the motor preventing blind intervals from occurring.

Magnets can also be attached to the rear motor shaft and sensed by various hall sensor arrangements (Fig.4 — Patent US6064197). The single magnet plus hall sensors have sufficient resolution for avoiding step loss, but (at the time of my most recent research for those showing accuracy specs) at ~ .2 degree max error (11 bit) may not be quite sufficient accuracy for high-performance commutation and control

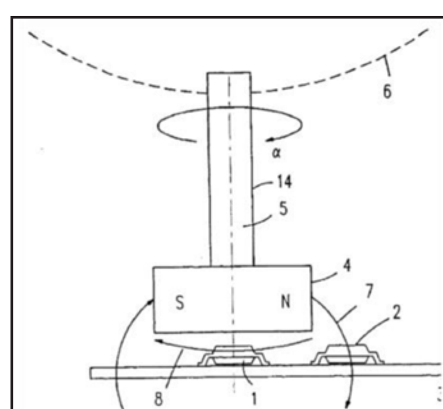

Figure 4 **Hall angle sensor with magnet.**

of the high pole count hybrid motors 1.8 degree motors. This area — like so many in motion control — continues to advance.

There are also electric field-based position sensors that use multiple, electrically conductive plates to resolve position. As with the resolver, the conversion time and phase implications of having "blind" periods in the conversion, as well as timing variations in the conversion sampling point, may hinder their use with the high-speed commutation of high-pole count motors. Again, the continuing advances may resolve these issues.

High-speed operation of these motors, for example a 1.8 degree motor at 4,000 rpm corresponds to

13,333-steps-per-second, or about 75uS per step (90 electrical degrees). Even a small variation in the sampling time of any sensor results in a variation in the measured position for that sample period from what the actual position measured would have been if it had been timely measured. The variation in measured position ends up varying the commutation angle, which causes a torque variation, and also varies the apparent velocity and position, both of which cause the control system to respond to the noise in these measurements, causing vibration in the operation of the motor. It is thus necessary to have a tight window on the sampling time of any of the position feedback devices used. With an 8,000-count-per-revolution encoder, for example, a 7.5uS variation in the sample time would correspond to 9 degrees of commutation angle and 8 counts of encoder error. One of the sensors examined had a sampling time uncertainty on the order of 100uS, so the sampling variation and latency are important specifications to investigate.

"Sensorless"

Multiple techniques use current sensing to estimate motor angle and/or velocity while the motor is in motion. These range from methods to improve damping to those that adjust the commutation points while moving to reduce loss of steps. The more advanced techniques use a Kalman filter to estimate the motor angle from the measured current versus the applied voltage using knowledge of the motor model.

A couple of other patents show integrating the voltage across the motor winding to estimate motor position from the integral of the back-EMF, while trying to compensate for the I*R voltage drops; another patent teaches the use of an 8-wire motor. One set of windings is used to drive the motor, and the second winding for each phase to directly sense and integrate the back-EMF, looking at the integral at of the back-EMF at points in time that the chopper is turned off (while recirculating).

Common to all back EMF techniques is the need for the motor to be in motion with enough velocity to induce a sufficient back-EMF for the measurement. For those measuring the back-EMF directly by monitoring the winding currents, the minimum speed to switch from open loop to closed loop can be significant. The final settling position of the motor is left to the motor torque stiffness curve, as the position when stopped is not able to be measured. This can leave significant position error in the presence of friction or load, as noted in the next section.

Torque versus Error in Open Loop Stepper

As stated earlier, there is a wide diversity of what is referred to as "closed loop" in the advertising of "closed loop" steppers and hybrid servo motors. This often leads to some confusion when comparing these systems to conventional servo motors. We will first review how torque is generated in the standard open-loop step motor, and then go into the range of modifications to these behaviors. For the comparison of closed loop stepper motors and hybrid servos, to simplify the discussion, we will assume (unless stated otherwise): 1) that we are using microstep-capable hybrid servos; 2) that the current to these motors is being controlled at a reasonable resolution to allow microstep; and 3) that any detent torque is significantly below the 100% torque level. We will also assume (for now) that 4) the drive voltage is high enough to properly control the current at speed, and 5) that the current vector length I_peak is held constant, with the two phases are driven as:

I_Aphase = I_peak * Sin (Theta)

And

I_Bphase = I_Peak* Cos (Theta)

Where "Theta" is the electrical angle of the motor which equals 50 *, the physical angle (for a 1.8 degree step motor).

First consider static winding currents (Theta constant). We describe the error angle as being the difference in actual electrical angle of the motor as

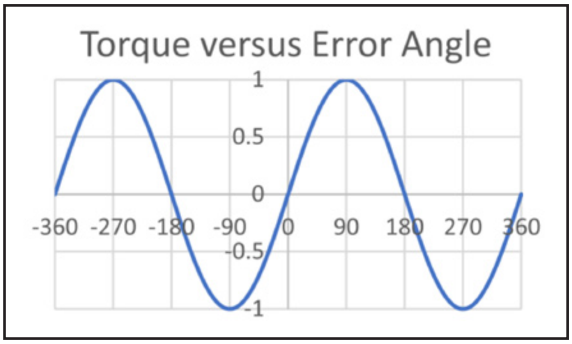

Figure 5 Torque vs error angle.

compared to the (friction-free) settling position of the motor for a given winding drive angle Theta. The torque generated is approximately a sine function of the error angle (Fig. 5). Zero error angle will produce zero torque. We consider the direction of error such that a positive torque will move the error angle value in a negative direction (to the left on the graph), while a negative torque will move the error in a positive direction (to the right on the graph). Thus, between -180 (electrical) degrees and +180 degrees of error, the resulting torque will try to drive error angle towards 0. For errors between -540 and -180, the torque will try to move the error toward the -360 degree point, while error angles between +180 and + 540 degrees will produce a torque which will try to move the error towards +360 degrees of error. Another way of stating this is that when the motor is energized in open loop, exceeding 180 electrical degrees (2 full steps) of error causes the motor to seek the next stable region, i.e. — 360 degrees or 4 full steps away — resulting in what is known as "losing steps."

Another important consideration is that generating 100 percent torque requires an error of (+/-) 1 full step (90 electrical degrees), and that any error except these points results in reduced torque. For stability of operation, the open loop stepper is typically used at between 25% and 30% of its full torque rating to avoid lost steps. The step sequence may also need careful attention, especially for high inertias.

Finally, notice that error *must* be present to produce *any* torque. Friction in the system will prevent the motor from actually reaching the zero error angle, and there will be two extreme resting positions, according to the direction of settling, i.e. — if the residual friction forces are positive or negative. If the load rings when settling in and/or there is significant friction, then there may be significant uncertainty in the final position of the motor even if the microstepping accuracy of the driving currents is perfect! Add the typical 5% step accuracy of the typical motor, and errors can accumulate quickly.

Closed Loop Stepper

The *zeroth* level of "closed loop" is to fix the motion after making it. The motion is made open loop and the result inspected, and then the motor is commanded to "fix" the motion so that the end position is close to the desired commanded move. Lost steps are corrected. The motor may overshoot significantly, or significant correction time may be needed if the motor lost sync early in the motion and the error was significant.

Mechanical collisions may occur and cutting edges may travel too far before being reversed. Liquid flow rates may not be consistent. Reversing of a pump after the liquid has been delivered will often not be effective in correcting the overshoot!

The *first* level of "closed loop" control is only asserted when the error of the motor reaches an error threshold point. (I think of it as open loop with guard rails; like you find on the kid's car rides at amusement parks. Not precise but it keeps you on the track!) For the early full step drivers this style of trajectory adjustment was used to keep the maximum error below 1.5 steps, allowing the motor to operate at the maximum average torque by jumping between .5 and 1.5 steps (1 step average). This same technique with a higher-resolution microstep drive limits the absolute value of the error to 90 electrical degrees or 1 full step, represented by Max T curve (Fig. 6).

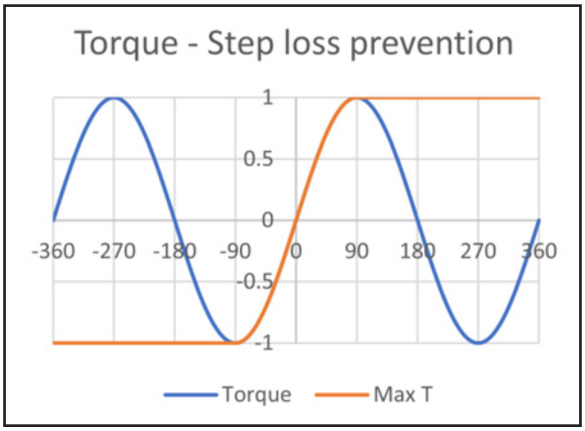

Figure 6 Peak torque closed loop stepper.

The trajectory generator controlling the current to the windings is modified by the feedback to prevent the difference between motor phasing and motor position from exceeding 1 full step, proving maximum torque for acceleration and deceleration. However, when the error is less than 1 full step, the motor reverts to open loop operation. This first level of closed loop has the advantage that no tuning is needed and the motor is prevented from losing steps. The feedback resolution requirement is typically lower, allowing lower-cost feedback. However, the open-loop issues with resonances (which include both vibration when running and ringing when settling), stopping error, stiction, and motor heating remain. No feedback loop is present to help reduce the position error at the end of travel, nor to help damp the oscillations of high-inertia systems. While some systems include the ability to drop the current to a lower holding level to reduce heating, the motor efficiency still remains quite low. High inertias may also get into a limit cycle where the error swings back and forth between the limits — both in motion and when the commanded motion has ended.

Some "sensorless" solutions only work in this first level of "closed loop," with the additional issue that they also lose the ability to prevent step loss at low speed where there is not sufficient back-EMF. Others go to the next level — at least while in motion.

The *second* level of "closed loop" is often called "field-oriented control." These operate the motor as a 2-phase brushless motor. The position information is used to commutate the motor, keeping the phase of the winding current in phase with the back-EMF to optimize the torque generation. (Field weakening used in more advanced field-oriented control makes this a bit more complex than described here, but that is another paper!) When less torque is required, the common method is to reduce the motor current vector, as commanded by a control law. There are patents which show the angle being reduced instead, such that the motor current remains constant (such as adjusting the angle of a microstep driver), and others that show a mix of the two, with both a current reduction and an angle reduction. Keeping the angle optimal and reducing the current is the most common method.

As field-oriented closed loop drives, the motor with only the current needed to produce the torque needed at that instant in time, the motor efficiency is significantly improved while also maximizing available motor torque. If field weakening is also implemented, then the motor speed and torque range can be significantly extended.

Full-Time Hybrid Servo

The highest stage is full time full servo control. This requires continuous monitoring of the rotor position so that the servo can control the error when the position is settling, as well as when the motor is in motion. It also commonly operates the motor using field-oriented control. A control law compares the actual and desired motion (position, velocity, and for some controllers, acceleration) and calculates the torque required to realize the desired motion (to the degree that it can). The torque can also be controlled, either as a limit or as a demanded value. This allows the error to approach zero even if the load on the motor is significant. Torque ripple can be minimized while the resulting speed can be made very steady. If there is sufficient damping in the system to allow the gain to be reasonably high, stiction can also be readily overcome. This is especially important when operating pumps (or other devices) with sliding seals.

Low-speed resonance. Low speed resonance is caused by the interaction of the open loop motor and the rotor inertia; Figure 6 shows the torque versus error angle. This same curve also (basically) applies when the motor is rotating (given the length of the current vectors remain constant). If the angle remains between +/- 90 degrees, we can approximate this as a k*theta spring (fairly accurately for small angles, not quite accurate for larger angles). This "spring" interacting with the rotary inertia of the motor forms a 2nd-order typically underdamped system. When the step rate hits the resonance frequency, a strong vibration can build up and the motor can lose in excess of ninety percent of its rated torque. The motor may lose sync all together.

If the same (microstep-rated) motor is sinusoidally commutated (i.e. — field-oriented control) using an angular position sensor, the torque remains almost constant as the motor is rotated (at least for lower speeds before the torque drops down). This looks like a simple force and an inertia (and a little damping) and the system looks first order. This does not have complex poles; the low-frequency resonance has thus been eliminated. This allows the motor to slowly ramp velocity without the noise and vibration that the low-speed resonance usually provides. Note that the zeroth and first-order "closed loop" stepper arrangements do not suppress this resonance.

Damping the Motor

The standard current-based choppers present the motor windings with a very high dynamic impedance. The bearings in most step motors are also commonly high quality, so they offer few losses. The basic motor and driver thus have very little intrinsic damping. Even with closed loop control, the system may exhibit relatively low damping. Although field-oriented control may reduce the low-frequency resonance, most motor systems drive some type of inertia through the springiness of the shaft and often a coupler. The motor inertia coupled through the spring of the shaft (etc.) to the load inertia forms another resonance (if not more than one if belts and pulleys are involved). These resonances can limit the gain allowable in the system before the system becomes noisy and finally unstable.

A viscous inertial damper shown (Fig. 7) (Patent US 4123675) may be added to the motor shaft to add mechanical damping to the system. The damper consists of a case surrounding an inertial ring which is coupled to the case by a viscous oil (or ferro fluid as in this patent).

The loose coupling through the oil is modeled as a dashpot coupling to the inertia ring. Any acceleration, including rotary oscillation of the shaft, will cause shearing of the viscous oil which will then couple torque to the inertial ring. If the motor speed is essentially stable, the inertial ring will come up to speed and will not put a continuous load on the shaft. The shearing which occurs when the inertia speed is not equal to the case speed dissipates power (p = torque * speed difference) into heating the oil. This provides significant damping to the motor system. The viscosity of the oil and the inertia of the ring can be varied to optimize the system. If you go through the math, this damping shows up as a significant phase boost in the system covering up to a couple of octaves width. The phase boost provided to the control system makes tuning the system much simpler, especially those involving significant inertias.

The PVIA (position, velocity, integral, acceleration) used by QuickSilver Controls simulates the torque reflected to the motor by a viscous inertial damper, allowing a very similar damping to be accomplished via software without the size and cost constraints of a physical viscous inertial damper.

QuickSilver Controls also breaks from most drive implementations by driving the motor with a PWM voltage mode technique which

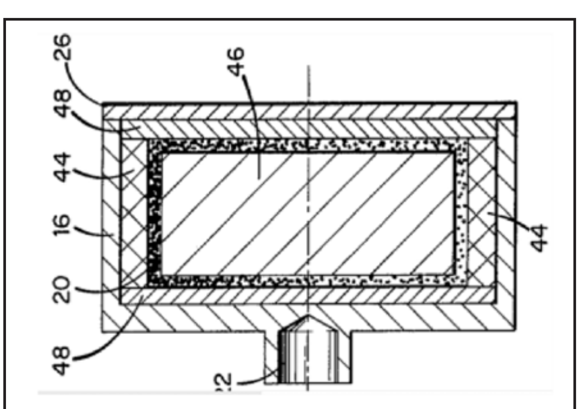

Figure 7 Viscous inertial damper.

approximates the high impedance of a current drive at lower frequencies while transitioning to a lower impedance of the voltage drive at higher frequencies. This allows normal torque control at the nominal movement frequencies while adding significant damping at higher frequencies where vibration may occur. To observe the damping present when driving these motors from a low-impedance source, short all the leads of a step motor and try to rotate the shaft. The significant damping will be immediately apparent. This voltage control method also eliminates the mid-frequency "resonance."

Results

The hybrid servo motors, when properly driven, are exceedingly responsive. Figure 8 shows a QCI-MV-23L-1 (1 stack NEMA 23 frame mosolver) doing a full revolution, start to stop, in 36 milliseconds. This is an acceleration from stopped to ~2,500 rpm in 12 milliseconds, slewing for 12 milliseconds, and then decelerating back to stopped in the final 12 milliseconds. The final settling is to within 45 counts (.5 mechanical degrees) over the whole last third of the motion, and to within approximately .1 degrees mechanical by 40 milliseconds. A 20-degree indexing takes about 7 milliseconds, depending on motor, load and power supply voltage used.

Proper driving of a hybrid servo motor can also provide high efficiency over a wide range of speeds. Figure 9 shows the measured efficiency of the X34HC-2 SilverMax integrated hybrid servo at various voltages. The efficiency includes both the motor and the driver losses. Efficiencies are between 70% and 85%, from a few hundred rpm through approximately 2,200 rpm. **PTE**

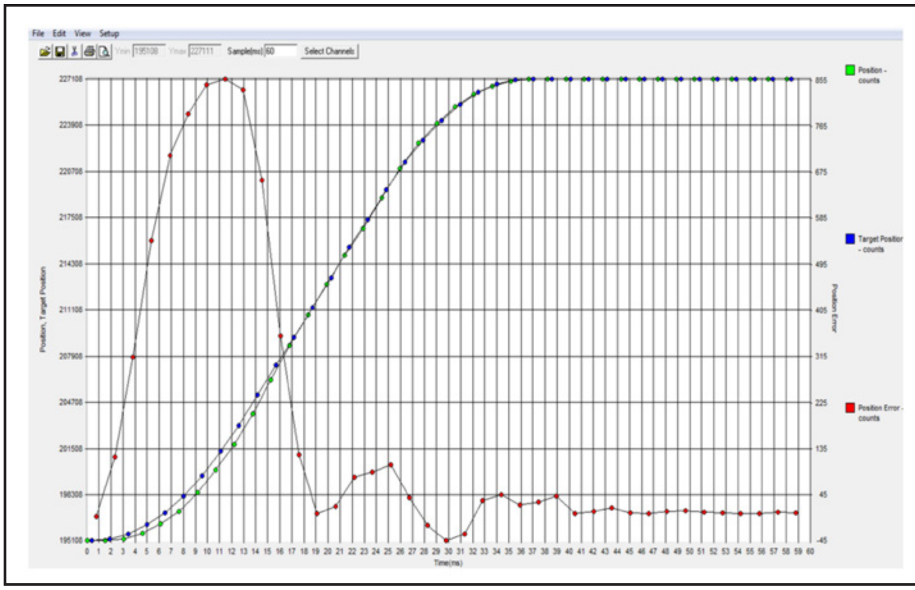

Figure 8 Rapid indexing of a QCI-MV-23L-1 mosolver.

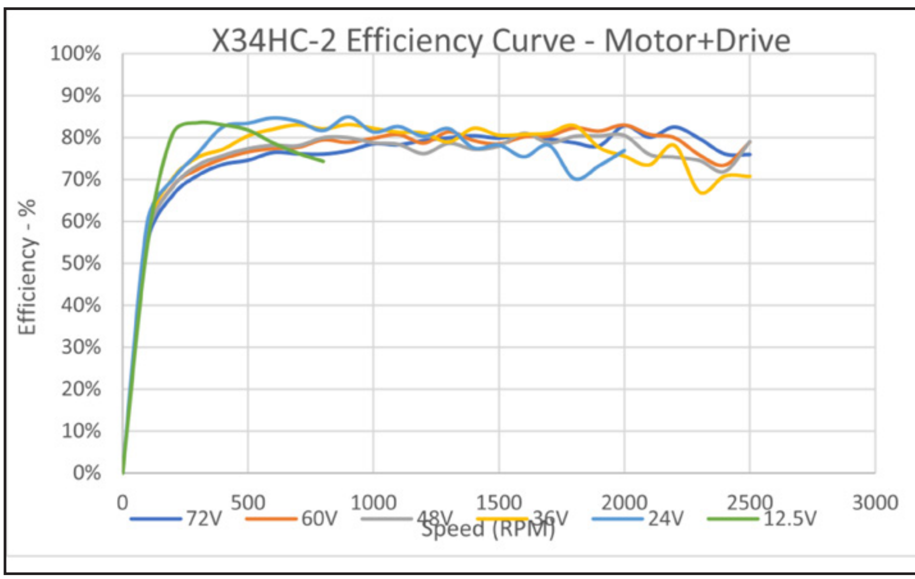

Figure 9 Efficiency versus speed.

Donald Labriola P.E. is president at QuickSilver Controls, Inc. He has been working with step motors since high school, and has had these motors operating field-oriented closed loop control since 1984.