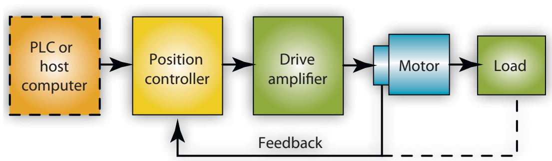
HANDBOOK FOR HIGH-PERFORMANCE BRUSHLESS SERVO SYSTEMS

This updated handbook provides a technical overview of the components, theory and interaction of brushless motion control systems.

Figure 1:
Block diagram of a typical motion control system



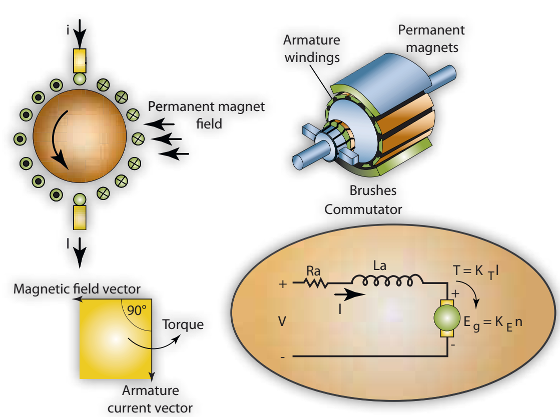
A simple representation of a typical motion control system is shown in Figure 1. Each of the primary components will be reviewed.

Theory of brushless motion control

Comparison of DC servomotors and brushless servomotors

The traditional permanent magnet DC servomotor has been the industry workhorse for many decades in high-performance servo drive applications. The primary reason for this is that the DC servomotor is very easy to control using adjustable DC voltage. A brief review of the operating principle of the DC motor illustrates this point: **See Figure 2.**

Figure 2:
Principle and construction of a DC Servomotor



A fixed magnetic field created by permanent magnets in the stator interacts with the armature current flowing in the rotor winding. Interaction of the current-carrying conductors in the magnetic field produces a rotor torque. This torque is at its maximum value when the magnetic field vector is perpendicular to the current vector, but is zero if the angle between the vectors is zero. The magnitude of the torque is:

$$\text{Torque} = K \bullet B \bullet I \bullet \sin \Theta$$

Where K is a constant, B is the magnetic flux density, I is the armature current, and Θ is the angle between the two vectors.

Therefore, as the rotor motion reduces the torque angle to a zero value, no further motion results. To eliminate this condition, the DC motor incorporates a commutator on the rotor, which routes the current flow in the armature windings as the rotor rotates. In other words, the current is progressively reversed as the windings connected to the commutator bars pass beneath the brushes. In a servomotor, the physical location of the brushes is such that the current vector is maintained perpendicular to the fixed magnetic field for any direction of rotor rotation or for any rotor speed. This results in torque generation proportional to armature current and motor speed proportional to armature voltage. The classic equations that describe the DC servomotor are then:

$$\text{Torque} = Kt \bullet I$$

$$Eg = \text{Back EMF Voltage} = Ke \bullet n$$

Where Kt is the torque constant, Ke is the voltage constant, and n is the motor speed.

While the control of a DC servomotor is straightforward, the primary limitation of the DC servomotor is the mechanical commutator. Some of these limitations include brush replacement, brush run-in after replacement, brush RFI (radio frequency interference) and voltage/current limitations. The construction of the DC servomotor also requires the commutator to rotate. This means the armature windings must rotate as well which results in high rotor inertia and a poor thermal situation because the heat from losses is primarily generated in the rotor. Of course, for any type motor, the heat-producing losses must be minimized and effectively transferred out of the motor so that temperatures inside the motor stay below maximum limits. Replacing the mechanical commutator with an electronic one can eliminate all of these DC motor limitations.

The electronically commutated motor or brushless servomotor consists of a permanent magnet rotor, a stator with usually three phases, and a rotor position sensor. **(See Figure 3.)**

Figure 3:
Principle and construction of a brushless servomotor

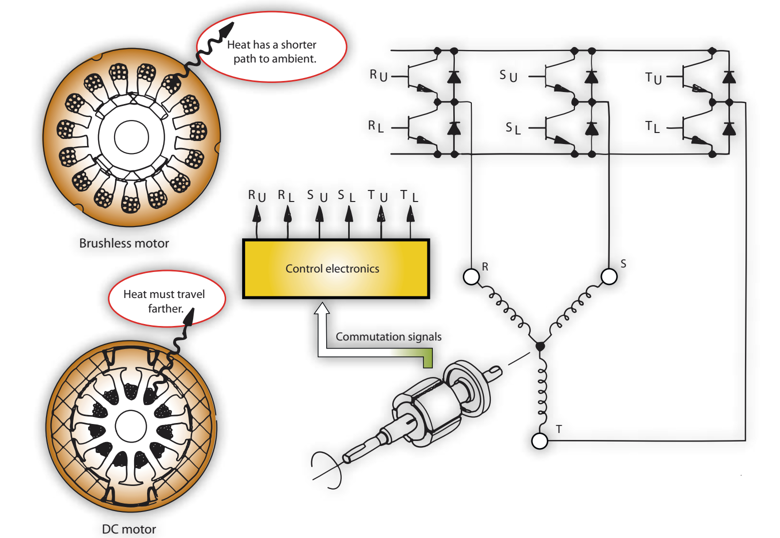
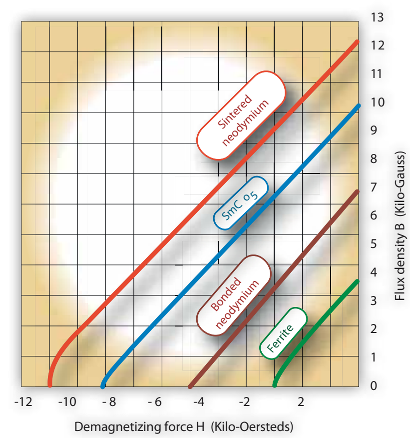


Figure 4:
B-H curves for permanent-magnet materials

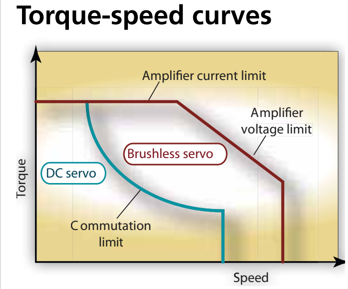


Due to the construction technique of a brushless servomotor (inside-out compared to the DC servomotor) the motor losses are almost entirely in the stator, resulting in a short thermal path to the ambient allowing more input power into the windings. Passing air over the motor frame can further increase heat transfer to the ambient. By eliminating the DC motor's mechanical commutator and armature winding on the rotor, the brushless motor design results in lower rotor inertias, higher rotor speeds, and higher motor supply voltages compared to the conventional DC servomotor. The polyphase stator winding for a brushless servomotor lends itself to automatic winding processes.

The permanent-magnet materials used for typical rotor construction are the rare earths (samarium cobalt and neodymium iron boron) or ceramic (ferrite). Typical demagnetization plots of the second quadrant B-H curves for these materials are shown in **Figure 4.** B is the flux density and H is the magnetizing force. The ferrite magnet has inferior magnetic properties, yet is low cost and readily available. The samarium cobalt material ($SmCo_5$) has excellent magnetic properties, can operate at higher temperature, but is expensive. The rare-earth material neodymium iron boron has many impressive magnetic properties. At the same time, however, there are limitations.

Neodymium iron boron magnet materials have less-than-optimal thermal properties and this must be taken into account in the motor design. Two forms of Neodymium iron boron magnets are shown in **Figure 4.** The highest performance is achieved with the fully dense sintered material. The bonded neodymium can be formed into more complex shapes simplifying manufacturing processes and lowering costs at the expense of performance. The rare-earth permanent magnets are used for high-performance brushless servomotors that have the lowest rotor inertias and the smallest overall motor size/ weight for a given torque rating.

Figure 5:
Torque-speed curves



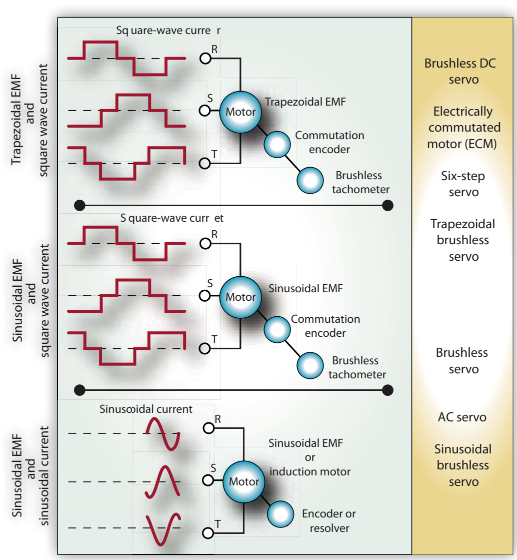
From an application perspective, the

torque-speed curves of a typical DC servo system versus a typical brushless servo system are shown in **Figure 5.** Note the ability of the brushless servo system to operate at higher speeds with higher peak torques compared to the conventional DC servo system. These advantages of electronic commutation versus mechanical commutation result in superior performance and reduced maintenance.

Sinusoidal and trapezoidal brushless servos

The basic structure of the DC servomotor and drive amplifier is relatively standard throughout the world. However, the same cannot be said about brushless servomotors and drive amplifiers. Some of the common brushless technologies and terminology are shown in **Figure 6.**

Figure 6:
Brushless drive technology and terminology



Trapezoidal EMF and square wave current

This type of brushless servo technology was developed first because of its analogy to traditional DC motors. The theory of operation is illustrated in **Figure 7.** As the rotor turns, the current is electronically commutated from one pair of windings to another. In this way, only the flattop portions of the back EMF are active, and a composite DC voltage is created proportional to motor speed. The current amplitude, which is proportional to developed torque, is usually controlled by pulse width modulating the active transistors. In practive, achieving the trapezoidal back EMF waveform imposes difficult motor design constraints. For this reason and because of the evolution of brushless servo technology (which we will descibe in following sections) this type of brushless servo drive is rarely used today.

ElectroCraft uses various neodymium iron boron magnets (rare earth magnets) in the ElectroCraft RP, RPP, and EXC families of brushless servomotors. The newer RP and RPP Series motor families were designed to exhibit superior velocity and torque performance, while maintaining a small footprint and competitive prices.

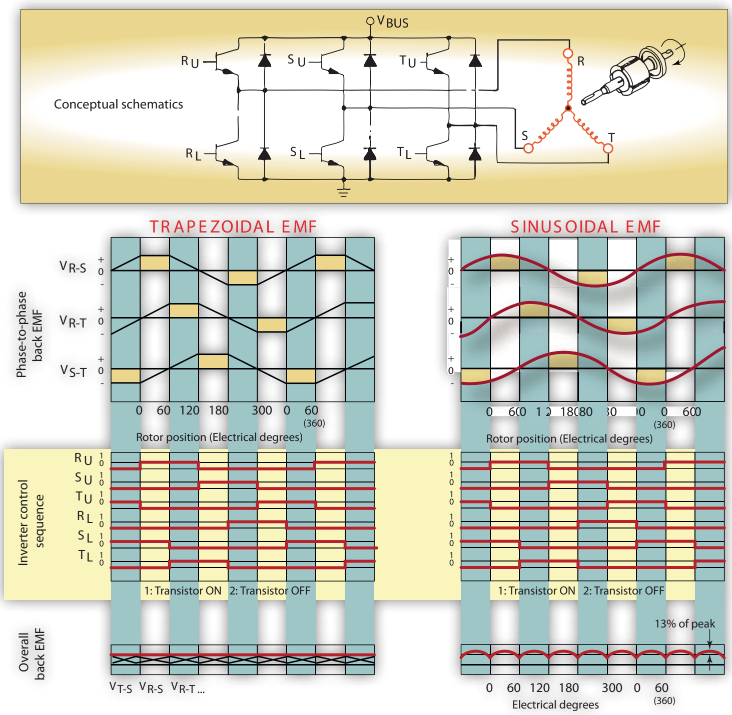
Sinusoidal EMF and square wave current

As stated previously, designing and manufacturing a brushless servomotor with trapezoidal EMF is not practical, so most brushless servomotors actually have sinusoidal back EMF. Because of the simplicity and low cost of the square-wave current control, it is common to have square-wave current servo amplifiers operating sinusoidal back EMF brushless motors. This is commonly referred to as a Brushless DC servo system. The theory of operation is shown in **Figure 7.**

Notice that with ideal back EMF and current waveforms, the motor torque constant Kt has a peak-topeak divided by peak ripple value equal to 13.4%. The average Kt value is about 10% higher than the Kt for sinusoidal currents. In closedloop velocity servos the Kt ripple is not necessarily a problem since a high velocity loop gain produces a very uniform rotation. However, the torque constant ripple does increase motor heating, because current is modulated by the ripple function to produce the uniform velocity. In fact, the continuous torque rating is decreased by about 5% as compared to sinusoidal current excitation.

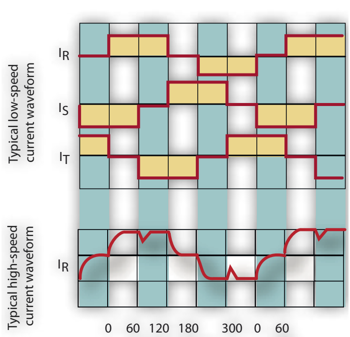
Another subject that has not been discussed yet is motor winding inductance. The coils of wire that make up the motor windings have resistance and inductance. From

Figure 7:
Waveforms for two EMF styles and square wave brushless servo drives



Faraday's law, current in an inductor cannot be changed instantaneously. In practice, the square wave currents suffer from the inductance effect – as shown in **Figure 8.** This torque loss progressively worsens as speed or frequency is increased. Phase advancing the commutation angle can improve this situation at the expense of additional complexity. In summary, excitation of a sinusoidal EMF brushless motor with a square wave current drive is practical and can result in acceptable performance for many applications. This very basic control principle is relatively simple to accomplish in a servo drive. This approach is still common and results in a lower cost solution, which requires less hardware and, in many cases, is simpler to install than more sophisticated brushless servo technology.

Figure 8:
Inductance effect with square wave current



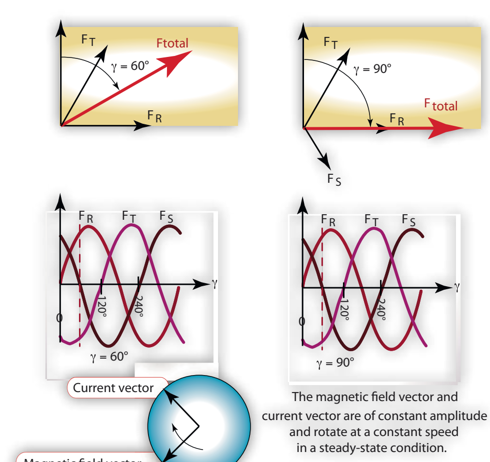
The ElectroCraft CompletePower™ series of brushless servo drives and speed controls utilize this control methodology. The Complete-Power Series of drives can be a cost effective and simple solution to many motion control applications.

Sinusoidal EMF and sinusoidal current

The sinusoidal brushless servo drive inherently results in the best rotational uniformity at any speed or torque. Compared to the pre vious technologies, the primary difference for the sinusoidal servo drive is a more complex control algorithm, while the motor, feedback, and power electronics remain the same. In recent years, the advancement of high-performance microcontrollers and Digital Signal Processors (DSPs) that now can handle complex calculations has increased the capability of the sinusoidal brushless servo system. The control hardware's capability combined with the decreasing cost of these components has driven further development of this control methodology above others previously described.

The sinusoidal back EMF motor excited with three phase sinusoidal currents (in the proper relationship to the back EMF at every rotor position) produces a constant torque. An explanation of this phenomenon at a steadystate speed and torque is illustrated in **Figure 9.**

Figure 9:
Sinusoidal three-phase principle of operation



The three-phase sinusoidal quantities – which are displaced spatially by 120° – represent the magnetic field and current. The three-phase quantities produce a resultant vector with constant amplitude that rotates at the sinusoidal frequency. The rotor position sensor tracks the back EMF position and allows the corrent vector command to be generated perpendicular to the magneticfield vector at any instand. A pulse width modulated (PWM) current amplifier is necessary to ensure the ability to control the current amplitude, frequency, and phase with sufficient dynamic performance. At this point, the fixed magnitude magnetic field vector, which is perpendicular to the adjustable magnitude current vector, is analogous to the operation of a DC motor.

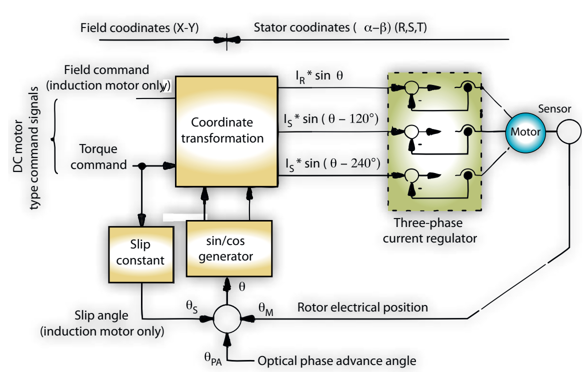
There are many brushless servo drives and brushless positioning drives that are designed to produce sinusoidal currents with incremental encoder feedback. This type of servo system combines the optimum motor design with a sinusoidal current PWM drives produce the best low-speed and high-speed performance. The ElectroCraft CompletePower™ Plus digital servo drive takes this control capability one step further. True sinusoidal current control can be accomplished in these drives without the need for high-resolution incremental encoder feedback. Only the lower resolution commutation feedback is required. In some applications, this reduces the need and cost of the additional encoder.

Other benefits resulting from the microprocessor-based drive design include the capability of operating induction motors using field oriented control and of sharing the motor mounted encoder with the position controller. This maximizes flexibility and performance and minimizes cost.

Sinusoidal control for permanent magnet brushless motors and induction motors

The mechanical commutator of the DC servomotor ensures that the armature current vector is kept perpendicular to the permanent magnet field at all speeds and torques. This provides for control of torque by simply adjusting the armature current level and makes using the DC servomotor very straightforward. Using input commands analogous to those for a DC servomotor, a universal control computes the torque producing sinusoidal currents for permanent-magnet brushless motors. (Otherwise, for induction motors, it computes the torque and field-producing sinusoidal currents.) This universal control strategy, known as field-oriented or vector control, is shown in **Figure 10.** Field-oriented control ensures that the torque-producing current vector is perpendicular to the field vector at any torque or speed. Some form of this control is used with all sinusoidal back EMF and sinusoidal current brushless servo drives. From the servo user's perspective, the torque, velocity, and position control is then analogous to the traditional DC servomotor.

Figure 10:
Field-oriented control for induction motors and permanent-magnet brushless motors



Also shown in **Figure 10** is an optional phase advance angle. The phase advance angle can be used to optimize the amplifier/motor performance characteristics. The most common use of the phase advance angle is to compensate for the inductance effect that causes a torque reduction as speed (frequency) increases. A less common use of the phase advance angle is to allow permanent magnet brushless motors to operate to a higher speed than would normally be possible without the phase advance angle. If the phase advance angle is used, the magnitude of the angle as a function of torque and/or speed is normally determined by the servo drive manufacturer and is not user adjustable.

Incremental encoders and resolvers

The most commonly used motor-mounted position feedback devices for sinusoidal brushless servos are either incremental optical encoders or brushless resolvers. The primary advantages of the resolver are that the position information is absolute and it is robust – because it is similar in construction to the motor. However, other factors favor the encoder over the resolver, including lower overall cost, digital feedback, higher resolution and accuracy, and easy line count flexibility (binary or decimal). The advancement of magnetic and capacitance-based incremental encoder technology further enhances the position of encoder feedback design, However, the use of both encoder and resolver feedback will likely continue into the foreseeable future as both solutions service the need of specific applications and operating environments.

The resolver used in brushless servo drives is illustrated in **Figure 11.** The high-frequency excitation signal is transferred to the rotor via a circular transformer. The raw resolver feedback is a high-frequency AC signal modulated by the sine and cosine of the rotor angle. The raw resolver feedback is not very useful, so some form of external circuitry is required to create usable information. In brushless servo drive applications the resolver feedback is usually processed by commercial resolver-to-digital-converters that add significant cost. The output of the resolver to digital converter is an absolute digital position word and analog velocity.

The incremental encoder used in brushless servo drives is illustrated in **Figure 12.** The raw encoder feedback, already in digital format, is typically processed with low-cost commercial circuitry to produce a digital position word. The position information interfaces directly to the microcontroller of digital drives. If the velocity loop is analog, then an additional circuit processes the encoder feedback to produce an analog tachometer signal. Notice that encoder feedback signals are differential, for high noise immunity, and for locating the encoder at long distances from the drive.

Figure 11:
Resolver feedback for brushless motors

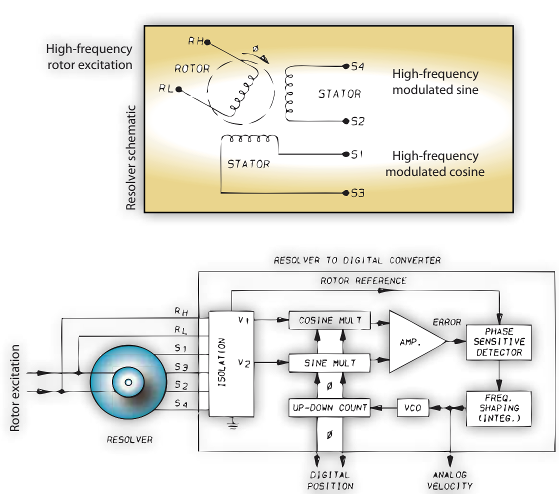
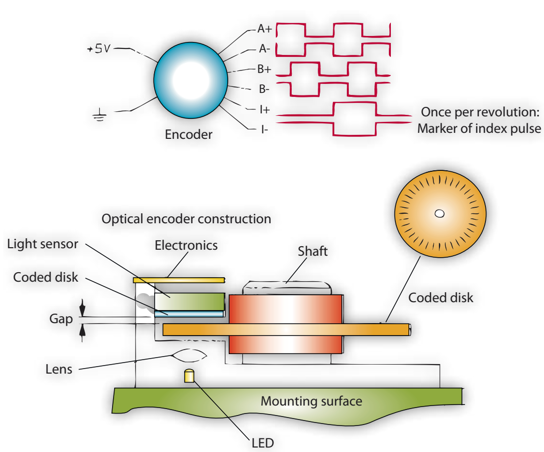
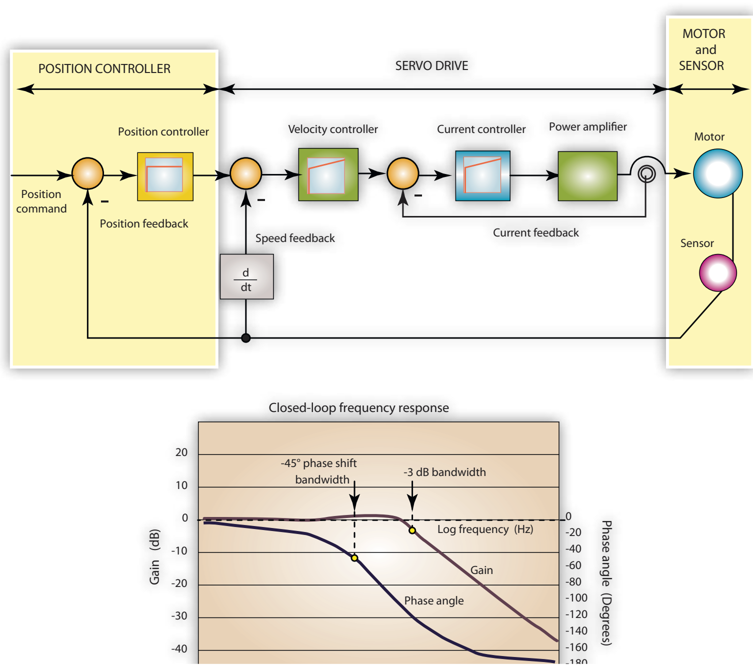


Figure 12:
Incremental encoder feedback for brushless motors



Permanent-magnet servomotors also use a low-resolution absolute signal in addition to the incremental encoder. This is used to locate the magnetic field vector at startup. The low-resolution absolute signal is often built into the incremental encoder (usually called commutation signals) or is generally provided from a separate Hall-effect, or commutation, encoder. In some cases, these commutation signals are incorporated into the incremental encoder and are provided by a single device, thus eliminating the separate commutation feedback device, reducing the cost and complexity of the servomotor design. Induction motors do not require an additional low-resolution absolute encoder because they do not use permanent magnets to establish the magnetic field vector.

Figure 13:
Closed-loop control for high-performance motion



Closed-loop control for high performance motion control, the most common structure for highperformance motion controllers, is illustrated in **Figure 13.** This cascade control structure has an innermost current loop, a velocity loop around the current loop, and a position loop around the velocity loop. The sequence of current (torque), velocity, and position is natural as it matches the structure of the process to be controlled.

This multi-loop control structure functions properly only if the bandwidths of the loops have the proper relationship.

Bandwidth is the measure of how well the controlled quantity tracks and responds to the command signal. **Figure 13** shows a closed loop frequency response and definitions for the two most common bandwidths – -3 dB bandwidth and -45° phase shift bandwidth. The current loop must have the highest bandwidth, then the velocity loop; finally, the position loop has the lowest bandwidth. Therefore, tuning control-loop regulators is accomplished by starting with the innermost loop and working outward.

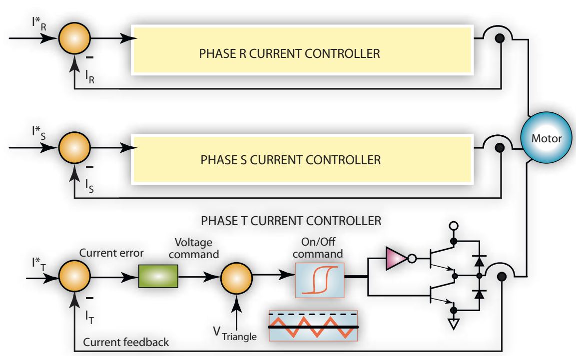
Current regulation

The current control for three-phase brushless servomotors is usually performed with a PWM power amplifier and closed-loop control of the current in each phase. A block diagram of the current loop and power amplifier is shown in **Figure 14.**

The power devices must be able to withstand high voltages, switch high currents, and exhibit low conduction and switching losses. Traditionally, the bipolar transistor and power field effect transistors (FETs) have been the most common output devices for high performance servo systems. However, these switches are being replaced with insolated-gate, biploar transistors (IGBTs) and intelligent power modules as these devices have lower losses and can operate at higher power levels. These devices combine the rugged output of a bipolar transistor with the gate drive and fast turn-off times of a power FET. The PWM frequency of modern servo drives is typically between 5 and 20 kHz. The high PWM frequency allows for a high current loop gain and keeps the current ripple frequency and audible noise to a low level.

The current feedback sensor is critical and must provide an exact representation of the actual current. The current feedback signal is compared to the current command to

Figure 14:
Three-phase current loop for a PWM power amplifier

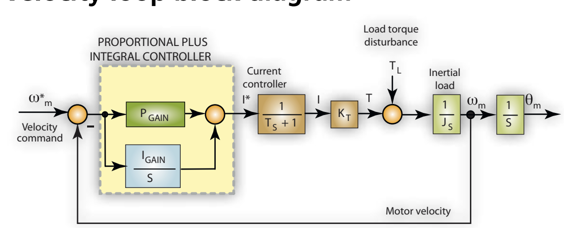


generate a current error signal. The current regulator processes current error to create a motor voltage command. The voltage command signal is compared to a triangle wave to create the PWM signal that commands the power devices to turn on and off at the proper time. There is additional circuitry that provides lockout to ensure that the upper and lower devices are never on at the same time, even during turn-off and turn-on transitions. Too much lockout time results in excessive deadband in the current loop while too little lockout time results in short-circuit or "shoot-through" current flowing through upper and lower devices. The PWM technique results in the most efficient conversion of DC to variable AC power.

Because the current controller tuning is very important for proper drive performance, most drive manufacturers do not allow users to perform this adjustment. In the past, to eliminate the need for current controller adjustments by the drive user, specific amplifier model numbers were matched with specific motor model numbers, or plug-in personality modules matched an amplifier with a motor. The next generation of ElectroCraft CompletePower™ Plus brushless servo motors and drives will self-detect the motor and drive combination and automatically determine the correct current control gain settings eliminating the possibility of incorrect setting. The end result of a properly tuned current controller is an actual current that follows the commanded current with -3 dB bandwidth commonly in excess of 1 kHz. To the outer velocity loop, a properly tuned current controller can be approximated by a fixed gain and first order lag such that the low frequency characteristics (up to frequencies of concern to the velocity loop) approximate the low frequency characteristics of the more complicated actual transfer function.

One limitation of the current loops is gain, phase, and offset errors that occur due to imperfect sensors and other circuitry. These errors are one source of torque ripple so it is important to keep these errors to an absolute minimum. Another limitation of the properly designed current controller is insufficient voltage to generate the necessary current. This situation occurs for large value current commands at higher motor speeds when the back EMF of the motor begins to approach the motor supply voltage. In applications requiring high torque at high speeds, careful observation of the motor/drive system peak torque envelope is required.

Figure 15:
Velocity loop block diagram



Velocity regulation and tuning guidelines

The most common velocity controller structure is the proportional plus integral (PI) regulator. A block diagram of a simple velecity loop appears in **Figure 15.** The choice of the P gain and I gain for the desired response are based upon the application requirements. Proportional gain is always used with higher bandwidths resulting from higher P gain values. The integral gain provides "stiffness" to load torque disturbances and reduces the steady-state velocity error to a zero value. However, integral gain does add phase shift to the velocity controller closed-loop frequency response and can lengthen settling time. Therefore, a low or zero-value integral gain is sometimes used with very high bandwidth position controllers in point-to-point positioning applications, while a significant integral gain value is used with contouring applications to provide high stiffness. In practice, the velocity controller tuning is rarely determined solely by calculation. Often tuning is done manually through trialand-error, with the motor connected to the actual load. This tuning is simplified though the use of sophisticated set-up software and a PC connected to the servo drive. The ElectroCraft CompletePower™ Set-Up Software Utility provides the user a manual tuning mode that allows a small step velocity command to be applied to the drive while the motor is attached to the actual load. Within the software utility, real-time adjustment of the velocity loop gains can then be made while observing oscilloscope waveforms on the PC to optimize the velocity loop tuning for the application. A typical example of velocity responses to the step changes in velocity command and load torque for a poorly tuned velocity loop and a well-tuned velocity loop are shown in **Figure 16.** Tuning should be performed with "small signal" responses – which means that the current stays away from the current limit at all times.

Figure 16:
Velocity responses to poorly tuned and well-tuned velocity loops

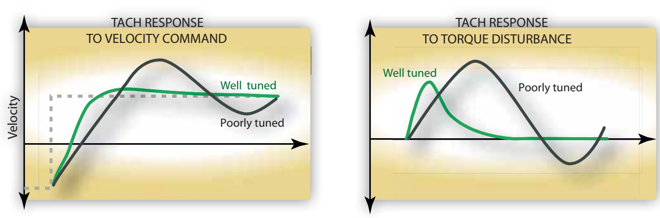


Figure 17:
Position controller block diagram

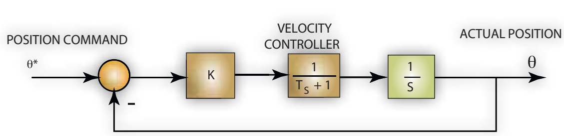
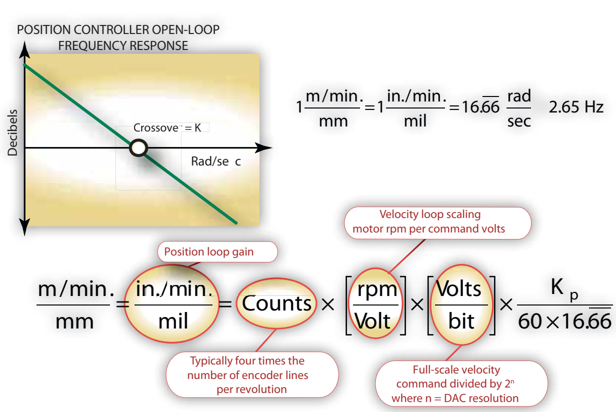


Figure 18:
Position controller response and Kp gain



Position regulator and tuning guidelines

Position control applications typically fall into two basic categories: contouring and point-to-point. Contouring applications require that the actual position follow the commanded position in a very predictable manner – with high stiffness to reject external torque disturbances. Notice that predictability is required, but this does not necessarily mean that position error must be zero at all times.

The other type of position control – point-to-point positioning – is typically defined by move time, settling time, and velocity profile, not paths.

Independent of the positioning application, the form of a simple position controller is shown in **Figure 17.** The velocity controller has been approximated by a unity gain and a first-order lag with a time constant equal to the velocity loop -45° phase shift bandwidth.

A position controller with only proportional gain K is very common (particularly for contouring applications), and the position loop response can be easily calculated for a certain crossover frequency or gain. The open-loop frequency response for the proportional position controller is shown in **Figure 18.** The crossover frequency is related to the common method of expressing gain:

2.65 Hz = 16.66 rad/sec =
1 inch/min./mil = velocity/position error

Where 1 inch/min./mil also equals 1 meter/min./mm. In most position controllers, the Kp gain is related to position loop gain as shown in Figure 18. A general position loop regulator is more complicated than the simple proportional gain-only type. The general position loop regulator is Proportional-Integral-Derivative with feed-forward (velocity and acceleration) and is illustrated in **Figure 19.** Following is a brief explanation of the purpose for the five adjustment terms.

phase-shift bandwidth cause actual position to overshoot the commanded position – which is usually undesirable. The feed-forward gain Kff generates a velocity command signal proportional to the derivative of the position command. Therefore, if there is no change in the position command, then the feed-forward command is always zero. Ideally, 100% feed-forward provides the exact velocity command without the need for any position error. In practice, actual systems including loads are not ideal, so a more conservative setting of feed-forward gain is often taken (100% or less) because too much feed-forward gain causes actual position to overshoot the commanded position. Because the feed-forward command is generated open loop, there is no effect on the position loop stability. The function of the feed-forward command is to significantly reduce the constant velocity following error even though the Kp gain is maintained at a proper level for stability. **Figure 20** shows an example of the feed-forward velocity

Figure 19:
General structure of position loop

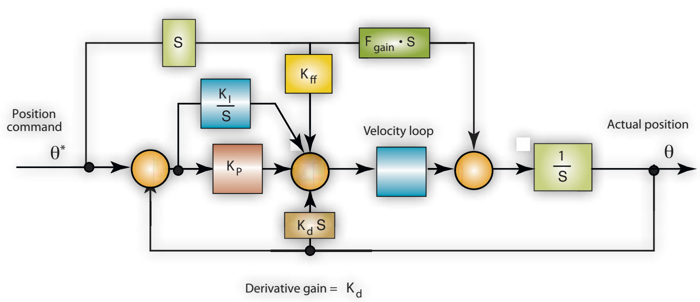
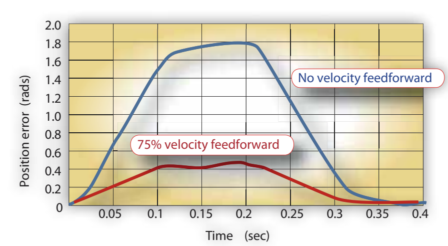


Figure 20:
Effect of velocity feedforward on position error profile



The proportional gain Kp is the most important term and generates a velocity command proportional to position error. In other words, if just Kp gain is present, motion is only possible if a position error exists. In fact, higher velocities result in proportionally higher position following error. Only increasing Kp gain can reduce the position following error. However, because the velocity loop has a given -45° phase-shift bandwidth, Kp gains that push position-loop bandwidth above about 1/3 of this velocity loop -45°

command effect on position following error when making a trapezoidal velocity profile move.

The derivative gain Kd as shown in Figure 19 creates a command signal that is proportional to the derivative of actual position feedback. The derivative term is used in two different situations. One situation occurs when the normal velocity servo is replaced by a torque (current) servo, which requires that the derivative term be used to provide the necessary damping in the form of a velocity feedback signal. The other situation occurs with a normal velocity servo to reduce overshooting of the position if a higher-than-normal Kp gain is necessary.

The next gain term is the acceleration feed forward gain, Fgain, which scales the second derivative of position command. This term allows position following error to be reduced when the velocity is changing. The acceleration feed-forward term is useful in combination with the velocity feed-forward term when trying to maintain a low following error at all times – which can be useful in tracking applications, or if a fast settling time is required.

The last term is the integral gain, Ki, which can provide a velocity command signal to reduce static position errors to zero. Integral gain provides stiffness against torque disturbances and friction torques and is usually handled in the velocity controller. Therefore, integral gain in the position controller is normally avoided except for special situations. Because integral gain causes overshooting, some position controllers with integral gain allow the integrator to only be active during certain conditions – such as when the position command is not changing, and when the actual position is very close to the commanded position.

For more Information:

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Web: www.electrocraft.com