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GALIL SUPPORT TEAM

[Webinar] Closed-Loop Control of Stepper Motors

Stepper motors are employed in a variety of applications across the engineering spectrum because they are inexpensive, simple to operate, and offer high torque at low speeds. However, stepper
motors suffer from drawbacks such as missed steps, decreased torque at high speeds, resonances, and high power consumption. In this webinar, three methods will be introduced that can be used to mitigate these issues by closing the loop around a stepper motor:

1. End-Point Correction
2. Closed-loop Microstepping
3. Controlling a Stepper Motor as a Brushless Motor

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https://webinars.on24.com/wtwh/ClosedLoopControl?partnerref=Galil
Transconductance vs Voltage Amplifiers

The purpose of an amplifier in a motion control system is to provide a controlled amount of current or voltage to a motor based on a command signal from the motion controller. This is done by a current (transconductance) or voltage amplifier. Each of these two types of amplifier has benefits and drawbacks which must be considered in order to choose the correct structure for a given motion control application. This paper will examine the similarities and differences between these two main types of switching amplifiers by addressing three key areas: performance, safety, and efficiency.

![Typical H-Bridge Circuit of Switching Amplifier](image)

Figure 1: Typical H-Bridge Circuit of Switching Amplifier

Switching amplifiers operate by turning each transistor either fully on or fully off and managing their duty cycles, the torque output from the motor can be controlled by the switching amplifier. It is worth mentioning that linear amplifiers on the other hand operate the transistors in their linear zone, where the transistors are turned partially on depending on the required output. Linear amplifiers are useful in applications where current ripple – the fluctuation in current due to switching – can be an issue, as well as for low power applications. However, because the transistors are being operated in their linear region, linear amplifiers are inherently inefficient. Due to their higher efficiency and usefulness for a wider range of applications, switching amplifiers are more common.
Basic Operational Principles

Switching amplifiers receive a command from a motion controller. This command can take the form of a digital word or an analog signal coming from a digital-to-analog converter (DAC). In both cases, the resolution of the command is typically 12 or 16 bit. For more information on how the resolution of the amplifier affects performance, see Galil’s Effects of Amplifier Resolution White Paper. Once received, this command is converted to the correct units and scaled by the amplifier’s gain. For a voltage amplifier this has units of volt/volt or volt/count, and similarly for a current amplifier has units of amps/volt or amps/count. Many amplifiers include configurable gains which should be chosen such that the maximum command from the motion controller results in the maximum required torque for a given application.

Once the command signal is properly converted, the amplifier then generates either a current or voltage to match the command. For the voltage amplifier, a duty cycle is generated such that the voltage output matches the voltage command. The current amplifier is slightly more complex, but ultimately a duty cycle is created based on the error measured between the actual output current and the commanded current. This current or voltage then creates a torque on the motor. The torque output of a motor is proportional to the current flowing through the motor’s windings multiplied by the motor’s torque constant as shown in Equation 1.

\[ T = K_T \times I \]

Equation 1: Motor Torque based on Current

\[ V = I \times R + \omega \times K_e + L \times \frac{di}{dt} \]

Equation 2: Motor Voltage

(cont. pg 5)
Based on Equation 2, there are three factors that influence the voltage across the motor. The first term, $I*R$ where $I$ is the current and $R$ is the motor resistance, represents the voltage drop due to the motor's resistance. Second, $\omega*Ke$, where $\omega$ is the rotational speed of the motor, and $Ke$ is the Back EMF constant of the motor, represents the voltage drop across the motor due to its speed. The third term, $L * \frac{di}{dt}$, where $L$ is the motor's inductance and $\frac{di}{dt}$ is the rate of change of the current in the motor, represents the voltage drop across the motor due to switching current. One important takeaway from this equation is that the maximum voltage output of the amplifier dictates the maximum speed the motor can reach based on its back EMF constant. Rearranging this equation gives a clearer look at how the voltage ultimately affects the torque of a motor, and is shown as Equation 3.

$$T = \frac{V - \omega * Ke - L * \frac{di}{dt}}{R} * K_T$$

Equation 3: Motor Torque based on Voltage

Performance

Now that the theory has been established for how voltage and current affects the torque of a motor, the ramifications of these equations on current and voltage amplifiers can be examined. Comparing the above equations gives a picture of one of the key differences between current and voltage amplifiers – linearity. Equation 3 shows that the torque created by a voltage amplifier is dependent on the speed of the motor. This means that the torque output will vary for a given voltage depending on the speed. Transconductance amplifiers do not suffer from this same issue as they control current directly.

Another important item is that voltage amplifiers operating in chopper mode are inherently non-linear when operating near the origin. In chopper mode, the amplifier sends a 0 to +V (where $V$ is the voltage applied to the transistors of the amplifier) PWM signal to the motor when moving in the forward direction, and a 0 to -V PWM to the motor when moving in the negative direction. Figure 2 shows the nonlinear response of a voltage amplifier running in chopper mode.
This behavior occurs when the current, which is created by the amplifier, reaches 0 between times when the transistors are turned on. When this occurs, the average current across the motor follows a quadratic curve rather than a linear curve. Linear behavior resumes as soon as the current waveform no longer reaches 0 between switches. Figure 3 demonstrates this concept.
Another key measurement of performance is bandwidth. There are two types of bandwidth that need to be addressed with respect to current amplifiers: current loop bandwidth and position loop bandwidth. Current loop bandwidth is a measurement of the ability of the current amplifier to react to changes to the commanded current. Position loop bandwidth is a measurement of the ability of the system being controlled to react to changes in the commanded position. In order for the position loop bandwidth to not be affected by the current amplifier, the current loop bandwidth should be an order of magnitude greater than the position loop bandwidth. Voltage amplifiers have no current loop, and thus do not have an equivalent issue. However, because the current amplifier is more linear than a voltage amplifier, higher position loop bandwidth can be achieved.

Safety

For the sake of safety, it is necessary to be able to limit the current output from the amplifier. Motors have two current ratings to be concerned with - a continuous rating and a peak rating. The average current in the motor must be kept at or below its continuous rating, whereas the peak rating deals with higher current over much shorter time periods. The reason for this is that as current is applied to the motor, the temperature of the motor will increase. If the temperature of the motor rises too high, the insulation on the motor coils will melt. Current amplifiers are able to ensure that the current in the motor never exceeds that which is requested by the motion controller because they are directly controlling the amount of current across the motor. This means that there is no risk of overheating the motor if the motion controller gives commands which are appropriate for the motor. Voltage amplifiers however do not naturally monitor current, and so there is the potential to overheat the motor if additional over-current protection is not present on the amplifier. This can happen if the motor stalls or becomes shorted, as well as if the commanded voltage causes an excessive current to be output to the motor. The Over-current circuitry adds additional cost and complexity to the voltage amplifier.

Similarly, over-voltage is a potential hazard to the amplifier itself. Motors can also act as a generator when trying to quickly decelerate if there is a large inertial load or if the motor is fighting large external forces. This power generated causes a problem because current is applied in the opposite direction of normal back through the amplifier and up to the power supply. This power has to be dealt with somewhere, and if the power generated is large enough to overcharge the capacitive elements in the circuitry damage will occur. In order to combat this, shunt regulators, or other protective circuitry, need to be added to both types of amplifiers.

Lastly, the reliability of each amplifier type is a key metric for safety. Voltage amplifiers construction is simpler than that of a current amplifier, and thus they can be slightly more reliable. However, reliability is primarily related to the power components of the amplifier, which are common between both current and voltage amplifiers.
Efficiency

The last topic which will be used as a benchmark for the comparison of voltage to current amplifiers is their efficiency. Efficiency is defined as the ratio of useful power generated to the total amount of power consumed as shown in Equation 4.

\[
\text{Efficiency} = \frac{\text{useful power}}{\text{total power}} \times 100\%
\]

Equation 3: Efficiency

Due to operating their transistors fully on or fully off, the efficiency of both types of switching amplifiers is typically greater than 90%.

Lastly, as a side-note, commutation of brushless motors adds some additional engineering challenge to current amplifiers which need to be overcome in order for them to properly deliver current to the motor. Commutation is the process of correctly energizing the brushless motor phases in order to rotate it. While both current and voltage amplifiers must commutate their output in order to correctly operate a brushless motor, current amplifiers must have additional current measuring circuitry in order to achieve this. This additional feedback must also be commutated for each phase of the motor so that it can be correctly scaled.

While transconductance and voltage amplifiers are identical when it comes to efficiency, the transconductance amplifier is a better choice for motion control applications due to its linearity and higher capability for position loop bandwidth. Though they do have some added complexity for commutation, this is outweighed by their performance benefits. Galil Motion Control is always ready to assist in determining the appropriate amplifier for even the most challenging motion control applications. If you have any questions about amplifiers, contact our Applications Engineering Department at (916) 626-0101 or by email at support@galil.com.
Forms of Closed Loop Stepper Control

Stepper motors are employed in a variety of applications across the engineering spectrum because they are inexpensive, simple to operate, and offer high torque at low speeds. However, stepper motors suffer from drawbacks such as missed steps, decreased torque at high speeds, resonances, and high power consumption. In order to mitigate these issues, Galil has three methods of closing the loop around a stepper motor: End point correction, closed loop microstepping, and driving the stepper motor as a 2-phase brushless motor.

Stepper Motor Basics

Stepper motors have multiple "toothed" electromagnets arranged around a gear-shaped rotor. To make the motor shaft turn, these electromagnets are energized in a specific sequence. Figure 1 shows a simplified view of this process for a 2-phase stepper motor. Each specific sequence corresponds to one step of the motor. A stepper motor typically has 200 steps per revolution.

Figure 1: Sample Full-Step Current & Rotor Position

(continuation on page 10)
Stepper motors do not come without some drawbacks. The first drawback of a stepper motor is that it operates at full current at all times. This leads to wasted energy and excess heat generation. Second, fundamental to the operation of stepper motors is the vibration caused when they change their position in discrete steps. When the step frequency matches the natural oscillation or resonant frequency of the stepper motor the amplitude of these vibrations will increase, leading to loss of position. Stepper motors also experience a significant torque decrease as the speed of the motor increases. A common speed-torque curve is shown in Figure 2. Lastly, the positional resolution is limited by the number of steps per revolution. If increased resolution is needed, the stepper can be driven through the process of microstepping.

![Figure 2: 24VDC Stepper Motor Speed-Torque Curve](image)

**Microstepping**

Microstepping is a method of driving a stepper motor such that every whole step of the motor is broken down into smaller increments called microsteps. Microstepping typically creates between 2 and 256 microsteps per full step which means that the 200 step per revolution motor can now have up to 51200 of these microsteps per revolution. Figure 3 details the current waveform through each stepper motor phase with an increasing number of microsteps per full step.

![Figure 3: Current Waveform during Microstepping](image)
The actual accuracy of microstepping is largely dependent on external forces. Microstepping is accurate to within a full step of the motor, however if more than a half step of error is present then loss of position will occur. Motion will not occur if friction, gravity, or any other force is large enough to prevent the small change in current between two microstepping positions from affecting the position of the motor. Figure 4 shows a plot of a point to point move executed in a system driven by a stepper motor coupled with an encoder. The red line is the expected position of the stepper motor, the purple line is the step pulses output to the motor, and the blue line is the motor position measured by the encoder. The black line indicates when the controller is actively profiling motion. Due to friction in the system, the stepper motor’s final position does not match the commanded position resulting in some steady state error.

Figure 4: Microstepping
End-Point Correction

By utilizing encoder feedback to recognize this position error, the end point can be adjusted by commanding additional step pulses to bring the motor into the correct position. Galil calls this Stepper Position Maintenance mode, or SPM. SPM still operates the stepper in the microstepping mode, but the endpoint accuracy can now be verified and adjusted. This mode works by comparing the commanded position of the stepper motor to the actual position output from the encoder just before completion of a move. Figure 5 shows the same system as Figure 4 now being operated in Stepper Position Maintenance mode. After the end of the move, the position error is recognized and the reference position is adjusted to account for this error. An error correction move is then commanded to bring the stepper to the correct position.

By adding the encoder, the controller now has the ability to recognize and correct for error present in the system. The same move which previously resulted in steady state error due to friction can now be accounted for and corrected.

Figure 5: Stepper Position Maintenance Mode

(cont. pg 13)
Closed-Loop Microstepping

SPM mode is intended for applications where the only concern is end point accuracy. When it is necessary to continuously correct for error, Galil offers Closed Loop Microstepping (CLS) mode. Figure 6 shows the stepper system now being driven in CLS mode. In addition to the reference position and encoder position, an error signal (green line) is now generated internally on the controller and is used to adjust the stepper motor’s position continuously. It is important to note that in CLS mode motion is now profiled based on the encoder position, but step pulses are still generated by the controller to drive the stepper motor.

![Figure 6: Closed Loop Microstepping](image)

The error signal generated is fed through Galil’s CLS filter which then compensates for any error present in the system by adjusting the step pulses output to the stepper. Closed Loop Microstepping is a true closed loop mode of operation, and is the optimum use of a stepper motor still being driven as a stepper. Closed loop operation brings with it the risk of instability if the loop is not correctly tuned, so care must be taken to achieve stability. Furthermore, this mode is still power inefficient and has low bandwidth when compared against a classic servo system. This low bandwidth can be made even lower when using external 3rd party stepper drives with low current loop bandwidth and non-linear characteristics.

> (cont. pg 14)
Driving a Stepper as a 2-Phase Brushless Motor

To achieve the highest performance, the stepper motor can be treated as a 2 phase brushless servo motor. Current to the motor will then be controlled as a function of the error signal just as with standard servo motors. Galil refers to as 2 Phase Brushless mode, or 2PB. Figure 7 details the stepper motor system being driven in this mode. Now, rather than step pulses, a torque command signal (brown line) is generated by the controller to be fed to one of Galil’s internal amplifiers operating in 2PB mode in order to control the position of the motor.

Running a stepper motor in this mode greatly improves its bandwidth, resulting in reduced move times. A stepper motor driven in 2PB mode is analogous to a classic servo motor attached to a speed reduction gearbox. Because this mode operates like a standard servo motor, the full range of Galil’s advanced PID filter capabilities can be now utilized, including the notch, pole, and feedforward filters. In order to drive the stepper motor in this way, the amplifier must be made more sophisticated to properly deliver only the instantaneous required current to the motor. This results in the stepper motor running power efficiently and causes it to generate far less heat.

Figure 7: 2-Phase Brushless Mode
Closed Loop Stepper Control

By leveraging Galil’s methods of closed loop stepper control, the various shortcomings of stepper motors can be overcome. The endpoint position can be adjusted for inaccuracies with stepper position maintenance mode, the position can be dynamically adjusted with closed loop microstepping, and lastly the stepper motor can be treated as a 2-phase brushless servo to further increase the performance and efficiency of the motor. If you have questions on which mode of closed loop stepper operation is appropriate for your application, contact our Applications Engineering department at (916) 626-0101 or by email at support@galil.com.

[App Note] Positioning a Stepper Motor Using Encoder Feedback on an Axis with Non-Linear Mechanics

The Closed-Loop Microstepping firmware is an excellent solution for applications that need end point accuracy when using stepper motors. However, this added complexity creates a challenge when tuning. This application note is designed to assist users in implementing and tuning the Closed-Loop Microstepping firmware.

For the full application note, see Application Note 5532:


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Our next two-day product school is Thursday August 3, 2017 through Friday August 4, 2017. The training will be at our headquarters in Rocklin, CA (near Sacramento). This technical training provides an overview of Galil products, a description of system elements, tuning, motion programming, software, troubleshooting, and hands-on labs. On the afternoon of the second day there is an opportunity to spend one-on-one time with the application engineers to ask additional questions or discuss individual applications. If you are a new user to Galil or want to learn more, signup now! For more information and to register go to http://www.galil.com/learn/classes or contact Mark Middleton at Mark.Middleton@galil.com. Please register by July 20, 2017.
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