DELTA TAU
Data Systems, Inc.

Digital Current Loops and Direct PWM Control

Until recently, digital control of a motor's current loop was not feasible – the required bandwidth of the current loop was too high for a cost-effective digital solution. However, with the advent of DSP technology, this has changed. Delta Tau has taken advantage of cutting-edge DSP technology to provide a very powerful, yet cost-effective, digital current-loop algorithm in its PMAC2 and Turbo PMAC2 line of controllers.

Digital Control Limitations

There are typically some disadvantages to digital control. First, the fact that the system is "sampled" at discrete intervals, and only one control decision is made per sample, adds a delay of half a sample cycle when compared to an analog loop. The time from when the feedback is sampled until the output is computed is a further delay, and any added time until the computed value actually appears as a signal would add yet more delay. Delays in a feedback loop limit the gain that can be achieved without repeatedly overshooting the mark.

Digital Control Advantages

However, digital control has many well-known advantages. Setting the gains can be much easier, a matter of changing numbers in registers instead of tweaking potentiometers. Gain settings can very easily be copied from system to system. The data logging capabilities of a digital system make it easy to store and plot key data for tuning and diagnostics.

In addition to these "standard" advantages of digital control, the use of digital current-loop control has several special advantages. Overwhelmingly, the power transistors in today's motor amplifiers are "pulse-width" modulated. Pulse-width modulation (PWM) is a digital technique; each power transistor is either fully on or fully off – the percentage of on-time determines the time-averaged voltage to the motor. Systems with an analog current loop must turn the loop's analog output back into a digital on-off signal. This, combined with the fact that the command input to the loop is from a sampled digital system, means that typical analog advantages are not present here. The digital loop eliminates the problems of imperfect digital-to-analog conversions into the loop and analog-to-digital conversions out of it, and of noise pickup on transmission of the analog signal.

(Linearly modulated power amplifiers remain for only a few "niche" reasons: for controlling motors with extremely low inductance, and therefore very short electrical time constants; for creating precision optical surfaces that cannot tolerate the minute vibration that PWM's on-off switching control introduces; and for processes that cannot tolerate the electromagnetic noise that the rapid switching of power transistors introduces. Some users of "sine-cosine" analog encoders for very high resolution feedback prefer linear amplifiers so they do not have to worry about special choking and shielding to keep this switching noise from getting into the feedback signals. For most people, the very high power losses of a linear amplifier are too much of a price to pay for these virtues.)

Furthermore, if the digital current loop is closed in the same processor as the position and velocity loops, calculation and propagation delays within the loops can be minimized. These delays are one of the key factors limiting gains in a servo loop, so reducing the delays permits higher gains yielding greater stiffness, bandwidth, and acceleration capabilities. Closing all of these loops synchronously with the PWM cycle eliminates the variable delays of loop closures asynchronous to the PWM cycle (where the worst-case delay determines the gain limitation).

AC Control Issues

Since the voltage and current in brushless motor phases is AC, the faster a motor moves, the higher the AC frequency. This has a couple of undesirable effects on traditional analog current loops. First, the loops fall behind at high frequencies. Second, the AC "back-EMF" waveforms created by the generator function of the motor create a high-magnitude high-frequency disturbance to the loop that makes it difficult for the loop to operate properly.

Digital control makes it possible to transform the AC current measurements into the frame of reference that rotates (or translates) with the magnetic field of the rotor, which is a "DC frame". Because the commanded current values are generated in this frame of reference, the current loops can be closed in this frame. This eliminates all of the AC problems in a single stroke, resulting in significant improvements in current-loop performance at high speeds.

Because of the transformation the current-loop algorithm performs, the loops that are closed are not those for phase currents, but for the torque-producing current component (perpendicular to the rotor's magnetic field) and the field-producing current component (parallel to the rotor's magnetic field). The field-producing current component is essential in the control of induction motors, which have no permanent magnets on the rotor; it can also be used in brushless servo motors to supplement or counteract the field from the magnets.

With the torque constant and back-EMF constant of the motor proportional to the net field strength of the rotor, having direct control of the field strength permits great flexibility in the operation of the motor. At low speeds, where the back EMF is not a problem, high field strength can be used to enhance the torque capabilities. At high speeds, low field strength can be used to reduce the back EMF and permit operation at higher speeds than otherwise possible.

Setup Issues

In this mode of control, virtually all differences between motors can be handled as software differences in the algorithm. Differences in electrical time constants are handled as just as differences in the numerical current-loop gains. Distinguishing between synchronous permanent-magnet servo motors and asynchronous induction motors is just a matter of different field-producing current parameters and rotor "slip" parameters. Different pole counts in motors just result in different parameters for commutation cycle size. Even the difference between brushed and brushless motors can be handled by changing the commutation cycle parameters. (With a brush motor, the motor leads are connected between two of the phases of the 3-phase amplifier; the third phase is left unused.)

With this scheme, the amplifier performs no control tasks. It becomes simply a "power block". Because of this, there is nothing to set in the amplifier: no potentiometer tweaking, no motor "personality modules", and no connection of a laptop computer to tune the amplifier. The amplifier is selected for voltage and current levels only. OEMs producing multiple units of a standard design do not have to set anything on, or load anything into, the amplifiers; in most cases the configuration into the controller is identical for all copies of the machine. A replacement amplifier can simply be connected into the system, with no further setup required.

Combining with High-Resolution Feedback

When this direct PWM technique is combined with very high-resolution feedback, as from a highly interpolated "sine-cosine" analog encoder, the gain improvements can be even greater. Resolution limitations are the other main factor in addition to delays that limit the gains in motion control systems. With rotary encoders, modern interpolation electronics can provide millions of states per revolution; with linear encoders, resolutions in the nanometer range can be achieved. These circuits provide so much resolution that gain limitations for this reason are essentially eliminated.

The advantages of direct PWM control and high-resolution feedback can be well illustrated in an example. A brushless motor was directly coupled to a screw driving a linear load. Quick indexing was desired, with the benchmark a 25-mm move settling to within two microns. Four control schemes were tried:

- Analog current loop, "times-4" decode: 130 msec
- Digital current loop, "times-4" decode: 100 msec
- Digital current loop: "times-256" interpolation: 75 msec
- Digital current loop: "times-4096" interpolation: 60 msec

First, note that the implementation of the digital current loop, which added no cost to the system, by itself provided a 25% reduction in time. Adding the high-resolution interpolation circuits, which does add cost, produces significant extra time savings.

Conclusions

Digital current-loop closure with direct PWM output provides many advantages to the motion control user, without adding cost to the system, and potentially reducing the cost. The reduced delays from integrated control permit higher gains and therefore "tighter" systems. The ability to transform the current values from AC to DC provides superior high-velocity performance. Setup is much easier, particularly for OEMs building large numbers of identical machines. Replacement of amplifiers in the field is much faster and easier.

21314 Lassen Street Chatsworth, CA 91311 / Tel. (818) 998-2095 Fax. (818) 998-7807 / www.deltatau.com