MACHINE DESIGN

 Machine Design (ISSN 0024-9114) is published semimonthly by Penton Media, Inc., 1100 Superior Ave., Cleveland, OH 44114-2543. Copies not qualified for domestic requester circulation: one year, $105; two years, $165.

Penton

Penton Media, Inc.

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Snake-oil specs spell trouble for motor sizing

A well-behaved motion system depends on motor parameters derived from lab tests. When critical ratings are suspect, run the tests and measure the results yourself.

One programmable drive can handle a wide variety of motors in a closed-loop motion system, provided it contains accurate values for electrical and mechanical time constants, peak power, peak torque, and motor constants. This Servostar drive, for example, controls brushless motors, direct-drive motors, and servomotors using parameters derived from tests routinely performed to set up drives for robust motion systems.

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When sizing and selecting small dc motors, various approaches can be used to determine electrical ratings and motor constants. Picking the wrong approach or using the wrong motor constant, however, can lead to a mediocre motion system. The data also can make comparisons between different manufacturers' motors grossly inaccurate. One way to ensure a robust motor-control system on the first pass would be to study all manufacturers' dc motor parameters, ratings, and tolerancing methods, and analyze their electrical and thermal effects. Also, analyze the tests that different manufacturers use to develop their motor parameters, then normalize the constants and evaluate the motors under one uniform set of conditions. The following details just such a procedure.

PERTINENT PARAMETERS

Five major parameters determine most motor constants needed to size a motor: torque sensitivity, K_t; resistance, R_m; peak current, I_p; inductance, L_m; and inertia, J_m. From these calculate peak torque, motor constant, response time, acceleration, time constant, and other performance factors using the *Motor parameter derivations* table. The same principles apply to linear-force motors, but rather than using rotational inertia and torque, calculate inertial mass and force.

Other critical factors, such as temperature rise per watt, cogging, viscous loss, ripple, friction, and motor weight let motion designers determine maximum duty cycle and output profiles to verify requirements. Regardless of the application, use parameter tolerances when calculating worst-case conditions.

Parameters for brushless dc motors powered by sine-wave drives differ from those controlled by conventional six-step dc pulse drives. And because a major trend is toward more brushless motors with resolver feedback, manufacturers are beginning to provide servomotor data sheets that list the torque sensitivity, K_t, in rms units to make the math easier when converting output torques and other parameters. Although other methods may be used to transform dc values into rms, it's not as simple as multiplying or dividing by a single factor. The *Sine-wave*

Common standards for dc-torque and brushless motors

TYPICAL DATA SHEET Motor size constants	Symbol	Tolerance	Stated condition
Peak torque	T_p	±10%	
Motor constant	K_m	nominal	@25°C
Electrical time constant	τ_e	nominal	
Mechanical time constant	τ_m	nominal	
Peak power input	P_p	nominal	stalled @25°C
Viscous damping, zero source impedance	F_0	nominal	
Viscous damping, infinite source impedance	F_i	maximum	
Motor friction torque	T_f	maximum	
Ripple torque, average to peak	T_r	maximum	percent
Temperature rise per watt	TPR	maximum	see note 1
Maximum winding temperature	—	maximum	
Rotor moment of inertia	J_m	maximum	
Max. power rate	P	nominal	
Max. theoretical acceleration	α_m	nominal	
No-load speed, theoretical	ω_{nl}	maximum	@V_p or specified mechanical speed limit
Motor weight	—	maximum	
WINDING CONSTANTS			
Dc resistance	R_m	±12.5% for brush motors ±10% for brushless	@25°C
Volts	V_p	nominal	@25°C
Current	I_p	rated	
Torque sensitivity	K_t	±10%	
Back-EMF	K_b	±10%	
Inductance	L_m	±30%	

Notes
1. TPR may be specified as mounted or unmounted. The difference between these two conditions makes a considerable difference in the value of TPR. To distinguish between these two symbols, a prime mark is applied to the mounted state, TPR′.
2. Unless otherwise stated, most parameters are specified at 25°C.

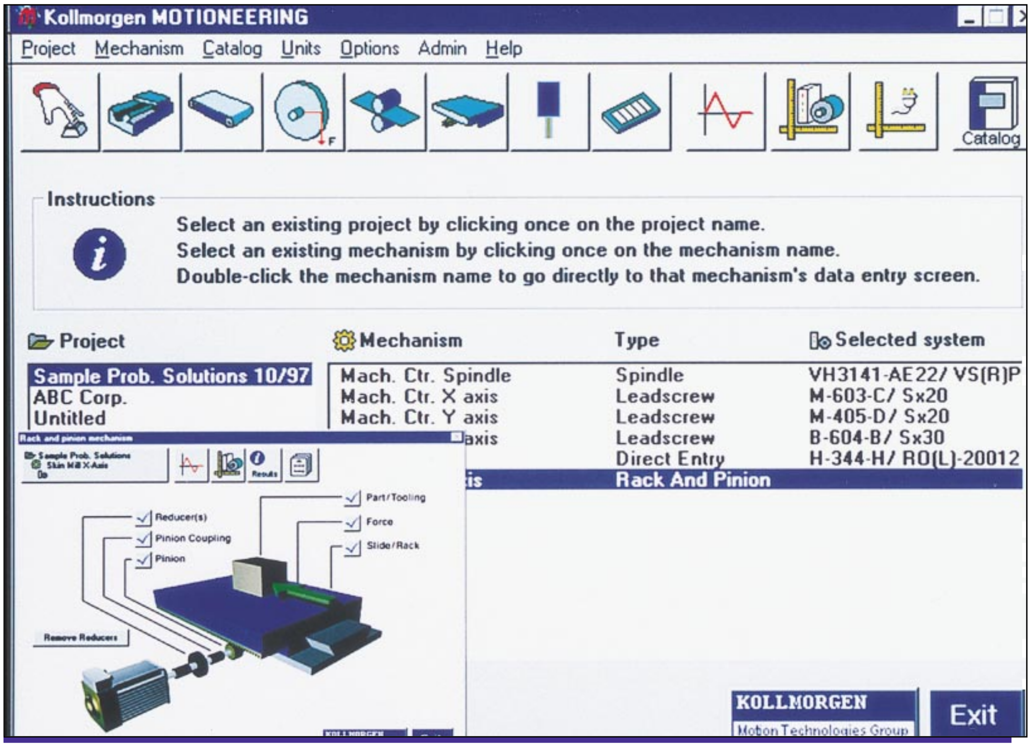
drive conversions table translates six-step to sine-drive parameters without first deriving multiplying factors.

Another approach that might prove misleading is a comparison among two or more motors, skewed by the test conditions under which the motors are rated. It's often difficult when comparing similar motors to understand why one appears to have greater peak torque, faster response, or higher acceleration. The first thought that comes to mind is that one motor is better than the other. Although each motor may be honestly rated and run at the nominal point of each specific parametric rating, the test conditions may differ enough to provide widely different values in a control system, thus creating an unfair or unbalanced data comparison. The only way out of this is to examine the different ratings and the various methods commonly used for tolerancing, and apply conversion factors or transformations to put them all on an equal footing.

For example, consider two motors of equal size using comparable design techniques and materials. Both motors dissipate the same power and have the same motor constant K_m, but one produces twice the peak torque. Checking out the test method might show that the higher torque came from twice the motor's rated peak current. Further examination may reveal that the higher rated unit can survive only when current peaks for less than one second, while the more conservatively rated motor may operate at its peak rating for several seconds.

FIRST-RATE MOTORS

One major rating method deals with motor input current, usually specified as a peak value. Occasionally, manufacturers provide continuous limits for constant-duty cycle or steady-state torque. Some push the peak current levels relatively hard. They are limited only by wire-current density or brush-current



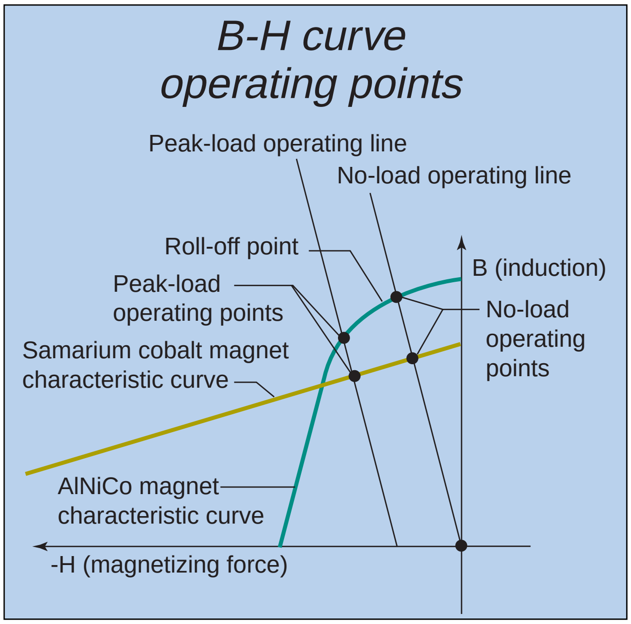
Numerous software packages are available to help take the drudgery out of defining motion profiles and selecting the optimum servomotor, amplifier, and power supply. Motioneering from Kollmorgen is such a tool on CD-ROM that runs in Windows. It calculates shunt regeneration for multiple axes, and simulates foldback circuits to ensure that the motor and amplifier combination considers the amplifier's time constant.

density in brushtype motors. A higher current generates more torque, although system efficiency doesn't improve because input power increases. This is why designers should compare motor constant K_m, a parameter independent of input power, to find a performance index for motor volume.

Also, look for current limits specified at the point where K_t rolls off because the motor saturates at that level, or at the knee of the B-H curve for the magnets used in the field assembly. Although the newer rare-earth magnets have a fairly straight load line in the second quadrant of the B-H curve as shown in the *B-H curve operating points*, many motors still use ceramic and AlNiCo magnets that partially demagnetize when exceeding the knee of the curve. Currents exceeding the peak rating generate high ampere-turns in the motor's armature and can drive the load point over the knee, permanently demagnetizing the motor's field assembly.

Even for rare-earth magnet motors, the load point may shift significantly on the B-H curve. Most often, this point rebounds up the curve with lower applied current. Some manufacturers specify K_t at the lower currents, producing a higher sensitivity because the flux density is higher. A more appropriate value is the flux point at peak current, I_p. Regardless of the current level up to rated peak, the motor reaches calculated minimum torque.

High current levels combined with a sufficient



number of turns in the winding may saturate the armature. This reduces K_t and makes the motor behave nonlinearly, much like the roll-off shown on the B-H curve. For example, consider a K_t = 10 oz-in./A at an input current of 5 A. At 50 A, the K_t might equal only 7 oz-in./A because the motor electromagnetically saturates. On the other hand, some published data sheets are accurate but show underrated motor performance. This is particularly true in the specialty motor business where ratings are often established from customer specifications rather than considering the full capabilities of a particular motor. Many of these motors might produce from 25 to 300% of rated torque. Although users may see this as an additional advantage, it makes a case for comparing the motor constant, K_m, and to avoid reviewing only one parameter.

Motor parameter derivations

MOTOR SIZE CONSTANTS	SYMBOL	DERIVED FROM
Peak torque	T_p	$K_t \times I_p$
Motor constant	K_m	$K_t/\sqrt{R_m}$
Electrical time constant	τ_e	L_m/R_m
Mechanical time constant	τ_m	J_m/F_0
Peak power input	P_p	$(I_p)^2 \times R_m$
Viscous damping, zero source impedance	F_0	K_tK_b/R_m
Viscous damping, infinite source impedance	F_I	Small % of F_0, test or estimated value
Motor friction torque	T_f	Test or estimate
Ripple torque, average to peak	T_r	Test or estimate
Temperature rise per watt	TPR	Test or estimate
Maximum winding temperature	—	Materials rated
Rotor moment of inertia	J_m	Calculated
Maximum power rate	P	$(T_p)^2/J_M$
Maximum theoretical acceleration	α_m	T_p/J_m
No-load speed, theoretical	ω_{nl}	Rated or calculated at some voltage by V/K_b
Motor weight	—	Calculated
WINDING CONSTANTS		
Dc resistance	R_m	Calculated
Volts	V_p	$I_p \times R_m$
Current	I_p	Rated
Torque sensitivity	K_t	Calculated
Back-EMF	K_b	$K_t \times$ constant*
Inductance	L_m	Calculated

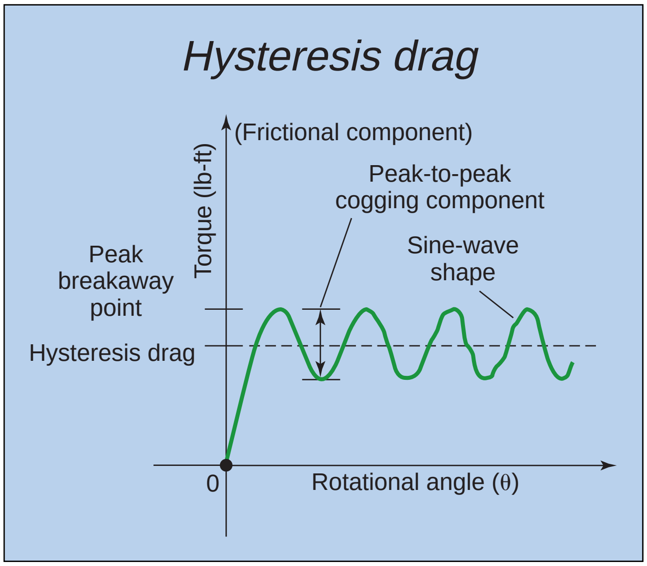
*K_t is proportional to K_b by a constant, depending on the system of units:
K_t (oz-in./A) × 0.00706 = K_b (V-sec/rad)
K_t (lb-ft/A) × 1.35582 = K_b (V-sec/rad)
K_t (mN-m/A) × 0.001 = K_b (V-sec/rad)
K_t (N-m/A) × 1.0 = K_b (V-sec/rad)

TOLERATE THE FIT

Most engineers design systems and components using worst-case tolerancing. Unfortunately, the method can oversize the system or understate the ultimate speed, torque, or acceleration. Often this happens when a motor manufacturer attempts to artificially position its product above the competition. Other firms design reliable motors and rate them conservatively while some advertise correct numbers under special conditions or at tolerance limits only, leaving little or no room for engineers to fine-tune the system.

For example, torque constant, K_t, typically comes with a ±10% tolerance. Although some manufacturers rate nominal K_t at the peak current, I_p, others list K_t at a smaller current, expecting it to remain within tolerance as the operating point shifts down the B-H load line with increasing current. This allows little remaining tolerance for the servo designer to manipulate at peak current conditions, and it worsens even more at elevated temperature. An industrial standard rates parametric values at 25°C ambient, but many change with temperature.

The effect of temperature on resistance is generally easy to understand, but its affect on torque loss in a motor is a bit more complex. For instance, the resistance of a motor initially starting in a room ambient temperature of 25°C, increases 50% when the winding reaches 155°C. Depending upon the magnet grade and motor's operating slope, torque sensitivity, K_t, can decrease from 3 to more than 20% over the same temperature range. Most manufacturers publish their motor ratings at 25°C because it's a traditional starting point. However, in servomotor applications where continuous duty is more typical, the magnets



are likely to see a higher temperature generated by armature heating. More conservative ratings and assurance that the user's load point will be met force manufacturers to specify the K_t at elevated temperatures. An example is a servomotor with continuous torque rated at 40°C. Only the motor manufacturer can accurately determine the derating factor because it knows the details of the motor design and materials.

Even more critical in determining whether or not a motor will achieve or even survive a continuous or stressful load condition is understanding the temperature rise per watt — the TPR parameter. However, when mounting the motor, it is conventional to specify the temperature rise with a prime mark in the symbol, TPR′. The unmounted motor is the worst-case condition, though most motors are mounted by some means. It's not unusual for the TPR to be reduced in smaller motors by a factor of 0.167 just by mounting, while air and fluid cooling reduce this value even more. The unmounted TPR is often stated on data sheets, particularly for frameless motors, because it provides a common baseline from which to estimate the derated value for specific mounting and environmental conditions. However, not all manufacturers follow this convention, so determine which temperature-rise factor is given before calculating duty cycles.

Another commonly misunderstood parameter is friction. Motor friction includes cogging, hysteresis loss, bearing friction (if housed), brush sliding contact friction (for brushtype motors) and a few other minor external influences. Most frictional components are widely understood, but the magnetically induced components of friction such as cogging and hysteresis losses often are not.

Cogging comes from changing reluctance paths while motor components rotate. When the field's magnetic poles pass the armature slot openings (air gaps) and approach the armature's metal teeth, magnetic force pulls the rotating part forward. It also grips the metal region and opposes the developed torque. A plot of this torque profile versus rotational angle looks like an erratic sine wave.

Hysteresis also plays a key role in establishing motor constants. It refers to the B-H loop of lamination material and flux density within the lamination region. It appears as a continuous component of friction even though it increases nonlinearly with frequency.

To see how this works, imagine a smooth ring with an inner multiple pole field assembly rotating at a steady speed. The magnetic flux produced by the magnets generates a frictional drag. The *Hysteresis drag* diagram typically illustrates the combination of these two elements' characteristics for most dc motors. Unfortunately, not all manufacturers' data sheets reflect the peak of these combined frictional components. The proper quantity to use is the starting break-away friction which includes the peak amplitude of the cogging component added to the hysteresis drag. ■

Sine-wave drive conversions

Six-step parameter (wye)	Multiply by	TO OBTAIN: Sine drive parameter
K_t (lb-ft/A)	$\sqrt{1.5}$	K_t (lb-ft/A rms)
R_m (Ω line to line)	0.50	R_{ph} (Ω/phase)
L_m (mH line to line)	0.50	L_{ph} (mH/phase)

OTHER USEFUL CONVERSIONS

K_t (lb-ft/A rms) × 81.97 = V/1,000 rpm (yields K_b constant)

K_t (lb-ft/A rms) × phase I_{rms} = Torque (lb-ft)

V_{IR} = phase I_{rms} × phase R_{ph} × $\sqrt{3}$

$V_{BEMF} = K_b \times S_{rpm}/1{,}000$

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