ENGINEERING BASICS

The following information helps you solve technical problems frequently encountered in designing and selecting motion control components and systems.

Torque

$$T = FR \qquad (1)$$

Where:
T = Torque, lb-ft
F = Force, lb
R = Radius, or distance that the force is from the pivotal point, ft

Linear to rotary motion

$$N = \frac{V}{0.262D} \qquad (2)$$

Where:
N = Speed of shaft rotation, rpm
V = Velocity of material, fpm
D = Diameter of pulley or sprocket, in.

Horsepower

Rotating objects:

$$P = \frac{TN}{5{,}250} \qquad (3)$$

Where:
P = Power, hp
T = Torque, lb-ft
N = Shaft speed, rpm

Objects in linear motion:

$$P = \frac{FV}{33{,}000} \qquad (4)$$

Where:
P = Power, hp
F = Force, lb
V = Velocity, fpm

Pumps:

$$P = \frac{QHS}{3{,}960\mu} \qquad (5)$$

Where:
P = Power, hp
Q = Flow rate, gpm
H = Head, ft
S = Specific gravity of fluid
μ = Pump efficiency

Fans and blowers:

$$P = \frac{Qp}{229\mu} \qquad (6)$$

Where:
P = Power, hp
Q = Flow rate, cfm
p = Pressure, psi
μ = Efficiency

Accelerating torque and force

Of rotating objects

$$T = \frac{(WK^2)\Delta N}{308t} \qquad (7)$$

Where:
T = Torque required, lb-ft
WK^2 = Total inertia of load to be accelerated, lb-ft^2. (See Formulas 9, 10, 11, and 12.)
ΔN = Change in speed, rpm
t = Time to accelerate load, sec

Objects in linear motion:

$$F = \frac{W\Delta V}{1{,}933t} \qquad (8)$$

Where:
F = Force required, lb
W = Weight, lb
ΔV = Change in velocity, fpm
t = Time to accelerate load, sec

Moment of inertia

Solid cylinder rotating about its own axis:

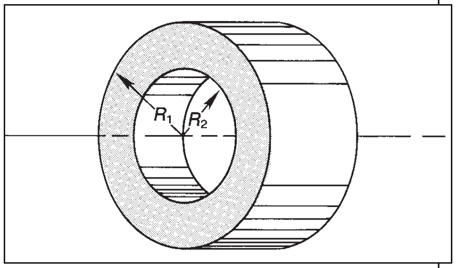
$$WK^2 = (1/2)WR^2 \qquad (9)$$

Where:
WK^2 = Moment of inertia, lb-ft^2
W = Weight of object, lb
R = Radius of cylinder, ft

Hollow cylinder rotating about its own axis:

$$WK^2 = \frac{W\left(R_1^2 + R_2^2\right)}{2} \qquad (10)$$

Where:
WK^2 = Moment of inertia, lb-ft^2
W = Weight of object, lb
R_1 = Outside radius, ft
R_2 = Inside radius, ft



Material in linear motion with a continuous fixed relation to a rotational speed, such as a conveyor system:

$$WK_L^2 = W\left(\frac{V}{2\pi N}\right)^2 \qquad (11)$$

Where:
WK_L^2 = Linear inertia, lb-ft^2
W = Weight of material, lb
V = Linear velocity, fpm
N = Rotational speed of shaft, rpm

Reflected inertia of a load through a speed reduction means — gear, chain, or belt system:

$$WK_R^2 = \frac{WK_L^2}{R_r^2} \qquad (12)$$

Where:
WK_R^2 = Reflected inertia, lb-ft^2
WK_L^2 = Load inertia, lb-ft^2
R_r = Reduction ratio

Duty cycle calculation

The RMS (root mean square) value of a load is one of the quantities often used to size PT components.

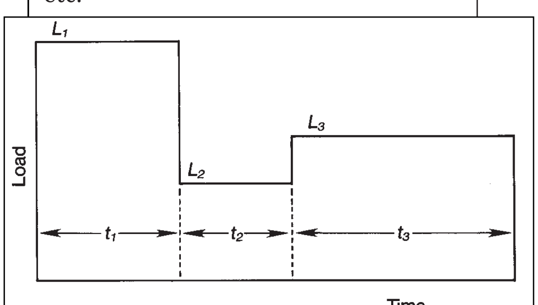
$$L_{RMS} = \sqrt{\frac{L_1^2 t_1 + L_2^2 t_2 + \ldots + L_n^2 t_n}{t_1 + t_2 + \ldots + t_n}} \qquad (13)$$

Mechanical properties of common materials

Material	Equiva-lent	Ultimate strength, psi: Tension	Ultimate strength, psi: Com-pression*	Ultimate strength, psi: Shear	Yield point, ten-sion (psi)	Modulus of elasti-city, tension or com-pression (psi)	Modulus of elasti-city, shear (psi)	Weight (lb per in.^{3})
Steel, forged-rolled								
C, 0.10-0.20	SAE 1015	60,000	39,000	48,000	39,000	30,000,000	12,000,000	0.28
C, 0.20-0.30	SAE 1025	67,000	43,000	53,000	43,000	30,000,000	12,000,000	0.28
C, 0.30-0.40	SAE 1035	70,000	46,000	56,000	46,000	30,000,000	12,000,000	0.28
C, 0.60-0.80	...	125,000	65,000	75,000	65,000	30,000,000	12,000,000	0.28
Nickel	SAE 2330	115,000	...	92,000	...	30,000,000	12,000,000	0.28
Cast iron:								
Gray	ASTM 20	20,000	80,000	27,000	...	15,000,000	6,000,000	0.26
Gray	ASTM 35	35,000	125,000	44,000	...	...	...	0.26
Gray	ASTM 60	60,000	145,000	70,000	...	20,000,000	8,000,000	0.26
Malleable	SAE 32510	50,000	120,000	48,000	...	23,000,000	9,200,000	0.26
Wrought iron	...	48,000	25,000	38,000	25,000	27,000,000	...	0.28
Steel cast:								
Low C	...	60,000	...	...	...	...	...	0.28
Medium C	...	70,000	...	...	...	...	...	0.28
High C	...	80,000	45,000	...	45,000	...	...	0.28
Aluminum alloy:								
Structural, No. 350	...	16,000	5,000	11,000	5,000	10,000,000	3,750,000	0.10
Structural, No. 17ST	...	58,000	35,000	35,000	35,000	10,000,000	3,750,000	0.10
Brass:								
Cast	...	40,000	...	...	...	...	...	0.30
Annealed	...	54,000	18,000	...	18,000	...	...	0.30
Cold-drawn	...	96,700	49,000	...	49,000	15,500,000	6,200,000	0.30
Bronze:								
Cast	...	22,000	...	...	...	...	...	0.31
Cold-drawn	...	85,000	...	...	...	15,000,000	6,000,000	0.31
Brick, clay	ASTM	...	1,500	3,000	...	...	...	0.72
Concrete 1:2:4 (28 days)	...	...	2,000	...	...	3,000,000	...	0.087
Stone	...	...	8,000	...	...	...	...	0.092
Timber	...	300	4,840	860	550	...	1,280,000	0.015

*The ultimate strength in compression for ductile materials is usually taken as the yield point. The bearing value for pins and rivets may be much higher, and for structural steel is taken as 90,000 psi.Source: S.I. Heisler, *The Wiley Engineer's Desk Reference*, 1984. Used with permission of John Wiley & Sons, New York.

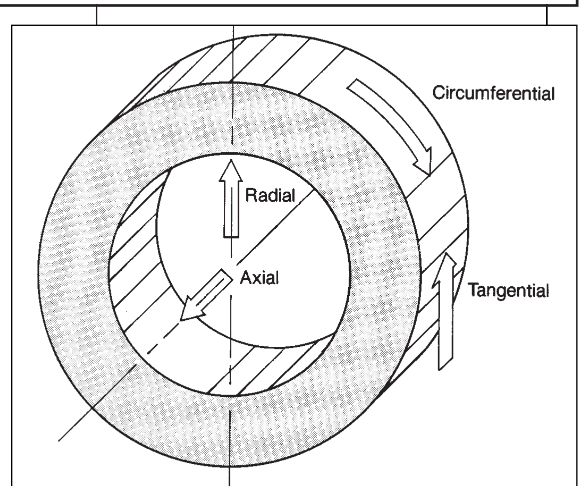
Where:
L_{RMS} = RMS value of the load which can be in any unit, hp, amp, etc.
L_1 = Load during time of period 1
L_2 = Load during time of period 2, etc.
t_1 = Duration of time for period 1
t_2 = Duration of time for period 2, etc.



Modulus of elasticity

$$E = \frac{PL}{A\Delta d} \qquad (14)$$

Where:
E = Modulus of elasticity, lb/in.^{2}
P = Axial load, lb
L = Length of object, in.
A = Area of object, in.^{2}
Δd = Increase in length resulting from axial load, in.



General technical references

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2. Hindehide, Zimmerman, *Machine Design Fundamentals,* John S. Wiley & Sons, New York, 1983.

3. K.M. Walker, *Applied Mechanics for Engineering Technology,* Third Edition, Reston Publishing Co. Inc., Reston, Va., 1984.

4. *ASM Handbook of Engineering Mathematics,* American Society of Metals, Metals Park, Ohio, 1983.

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MOTION CONTROL BASICS

The first step in determining the requirements of a motion-control system is to analyze the mechanics — including friction and inertia — of the load to be positioned. Load friction can easily be determined either by estimating or by simply measuring with a torque wrench.

Inertia — the resistance of an object to accelerate or decelerate — defines the torque required to accelerate a load from one speed to another, but it excludes frictional forces. Inertia is calculated by analyzing the mechanical linkage system that is to be moved. Such systems are categorized as one of four basic drive designs: direct, gear, tangential, or leadscrew.

In the following analyses of mechanical linkage systems, the equations reflect the load parameters back to the motor shaft. A determination of what the motor "sees" is necessary for selecting both motor and its control.

Cylinder inertia

The inertia of a cylinder can be calculated based on its weight and radius, or its density, radius, and length.

Solid cylinder, Figure 1.
Based on weight and radius:

$$\frac{NL - N_{FL}}{N_{FL}} \times 100$$

Based on density, radius, and length:

$$J = \frac{\pi L \rho R^4}{2g} \qquad (2)$$

Hollow cylinder, Figure 2.
Based on weight and radius:

$$J = \frac{W}{2g}\left(R_o^2 + R_i^2\right) \qquad (3)$$

Based on density, radius, and length:

$$J = \frac{\pi L \rho}{2g}\left(R_o^4 - R_i^4\right) \qquad (4)$$

With these equations, the inertia of mechanical components (such as shafts, gears, drive rollers) can be calculated. Then, the load inertia and friction are reflected through the mechanical linkage system to determine motor requirements.

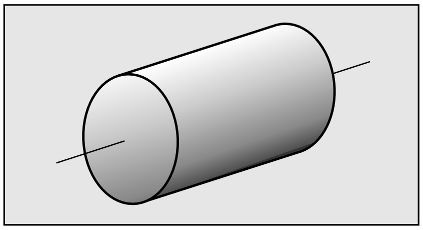


Figure 1 — Solid cylinder.

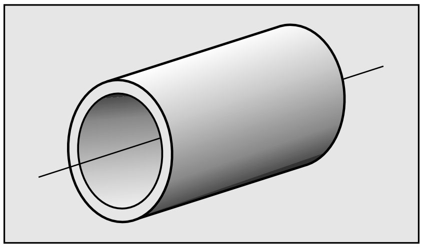


Figure 2 — Hollow cylinder.

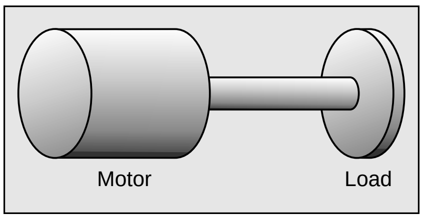


Figure 3 — Direct drive. Load is coupled directly to motor without any speed changing device.

Example: If a cylinder is a leadscrew with a radius of 0.312 in. and a length of 22 in., the inertia can be calculated by using Table 1 and substituting in equation 2:

$$J = \frac{\pi L \rho R^4}{2g} = \frac{\pi(22)(0.28)(0.312)^4}{2(386)}$$

$$= 0.000237 \text{ lb-in.-sec}^2$$

Direct drive

The simplest drive system is a direct drive, Figure 3. Because there are no mechanical linkages involved. The load parameters are directly transmitted to the motor. The speed of the motor is the same as that of the load, so the load friction is the friction the motor must overcome, and load inertia is what the motor "sees." Therefore, the total inertia is the load inertia plus the motor inertia.

$$J_t = J_l + J_m \qquad (5)$$

Nomenclature:

- α_{acc} = Rotary acceleration, rad/sec^2
- e = Efficiency
- F_l = Load force, lb
- F_f = Friction force, lb
- F_{pf} = Preload force, lb
- g = Gravitational constant, 386 in./sec^2
- I_{acc} = Current during acceleration, A
- I_{rms} = Root-mean-squared current, A
- J = Inertia, lb-in.-sec^2
- J_{ls} = Leadscrew inertia, lb-in.-sec^2
- J_l = Load inertia, lb-in.-sec^2
- J_m = Motor inertia, lb-in.-sec^2
- J_t = Total inertia, lb-in.-sec^2
- J_p = Pulley inertia, lb-in.-sec^2
- K_t = Torque constant, lb-in./A
- L = Length, in.
- μ = Coefficient of friction
- N = Gear ratio
- N_l = Number of load gear teeth
- N_m = Number of motor gear teeth
- p = Density, lb/in.^{3}
- P = Pitch, rev/in.
- P_{del} = Power delivered to the load, W
- P_{diss} = Power (heat) dissipated by the motor, W
- P_p = Total power, W
- R = Radius, in.
- R_i = Inner radius, in.
- R_m = Motor resistance, Ω
- R_o = Outer radius, in.
- S_l = Load speed, rpm
- S_m = Motor speed, rpm
- t_{acc} = Acceleration time, sec
- t_{dec} = Deceleration time, sec
- t_{idle} = Idle time, sec
- t_{run} = Run time, sec
- T = Torque, lb-in.
- T_{acc} = Acceleration torque, lb-in.
- T_{dec} = Deceleration torque, lb-in.
- T_f = Friction torque, lb-in.
- T_l = Load torque, lb-in.
- T_m = Motor torque, lb-in.
- T_r = Torque reflected to motor, lb-in.
- T_{rms} = Root-mean-squared torque, lb-in.
- T_{run} = Running Torque, lb-in.
- T_s = Stall torque, lb-in.
- V_l = Load speed, ipm
- W = Weight, lb
- W_{lb} = Weight of load plus belt, lb

Gear drive

The mechanical linkages between the load and motor in a gear drive, Figure 4, requires reflecting the load parameters back to the motor shaft. As with any speed changing system, the load inertia reflected back to the motor is a squared function of the speed ratio.

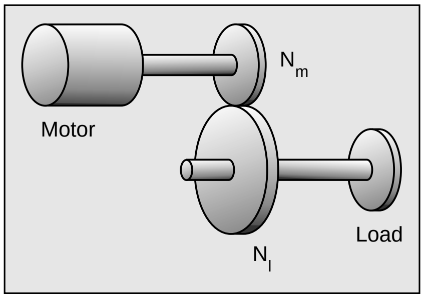


Figure 4 — Speed changer between load and motor. Any speed changing device — gearing, belt, or chain — alters the reflected inertia to the motor by the square of the speed ratio.

Motor speed:

$$S_m = S_l \times N \quad (6)$$

or

$$S_m = \frac{S_l \times N_l}{N_m} \quad (7)$$

Motor torque:

$$T_m = \frac{T_l}{Ne} \quad (8)$$

Reflected load inertia:

$$J_r = \frac{J_l}{N^2} \quad (9)$$

Total inertia at motor:

$$J_t = \frac{J_l}{N^2} + J_m \quad (10)$$

Example: To calculate the reflected inertia for a 6-lb, solid cylinder with a 4-in. diameter, connected through a 3:1 gear set, first use equation 1 to determine the load inertia.

$$J_l = \frac{WR^2}{2g} = \frac{6(2)^2}{2(386)}$$

$$= 0.031 \text{ lb-in.-sec}^2$$

To reflect this inertia through the gear set to the motor, substitute in equation 9.

$$J_r = \frac{0.031}{3^2} = 0.0034 \text{ lb-in.-sec}^2$$

For high accuracy, the inertia of the gears should be included when determining total inertia. This value can be obtained from literature or calculated using the equations for the inertia of a cylinder. Gearing efficiencies should also be considered when calculating required torque values.

Tangential drive

Consisting of a timing belt and pulley, chain and sprocket, or rack and pinion, a tangential drive, Figure 5, also requires reflecting load parameters back to the motor shaft.

Motor speed:

$$S_m = \frac{V_l}{2\pi R} \quad (11)$$

Load torque:

$$T_l = F_l R \quad (12)$$

Friction torque:

$$T_f = F_f R \quad (13)$$

Load inertia:

$$J_l = \frac{W_{lb} R^2}{g} \quad (14)$$

Total inertia:

$$J_t = \frac{W_{lb} R^2}{g} + J_{p1} + J_{p2} + J_m \quad (15)$$

Example: A belt and pulley arrangement will be moving a weight of 10 lb. The pulleys are hollow cylinders, 5-lb each, with an outer radius of 2.5 in. and an inner radius of 2.3 in.

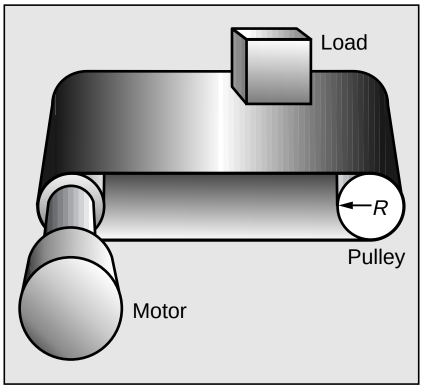


Figure 5 — Tangential drive. The total load (belt plus load) is moved with a lever arm with a radius, *R*.

To calculate the inertial for a hollow, cylindrical pulley, substitute in equation 3:

$$J_p = \frac{W}{2g}\left(R_o^2 + R_i^2\right) = \frac{5}{2(386)}\left(2.5^2 + 2.3^2\right)$$

$$= 0.0747 \text{ lb-in.-sec}^2$$

Substitute in equation 14 to determine load inertia:

$$J_l = \frac{WR^2}{g} = \frac{10(2.5)^2}{386}$$

Total inertia reflected to the motor shaft is the sum of the two pulley inertias plus the load inertia:

$$J = J_l + J_{p1} + J_{p2}$$

$$= 0.1619 + 0.0747 + 0.0747$$

$$= 0.3113 \text{ lb-in.-sec.}^2$$

Also, the inertia of pulleys, sprockets or pinion gears must be included to determine the total inertia.

Table 1—Material densities

Material	Density, lb per cu in.
Aluminum	0.096
Copper	0.322
Plastic	0.040
Steel	0.280
Wood	0.029

Table 2—Typical leadscrew efficiencies

Type	Efficiency
Ball-nut	0.90
Acme (plastic nut)	0.65
Acme (metal nut)	0.40

Table 3—Leadscrew coefficients of friction

Steel on steel (dry)	0.58
Steel on steel (lubricated)	0.15
Teflon on steel	0.04
Ball bushing	0.003

Leadscrew drive

Illustrated in Figure 6, a leadscrew drive also requires reflecting the load parameters back to the motor. Both the leadscrew and the load inertia have to be considered. If a leadscrew inertia is not readily available, the equation for a cylinder may be used.

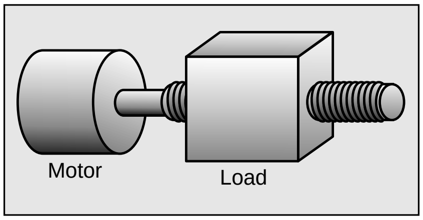


Figure 6 — Leadscrew drive.

For precision positioning, the leadscrew may be preloaded to eliminate or reduce backlash. Such preload torque can be significant and must be included, as must leadscrew efficiency.

Motor speed:

$$S_m = V_l \times P \qquad (16)$$

Load torque reflected to motor:

$$T_r = \frac{1}{2\pi}\frac{F_l}{Pe} + \frac{1}{2\pi}\frac{F_{pf}}{P} \times \mu \qquad (17)$$

For typical values of leadscrew efficiency (e) and coefficient of friction (μ), see Tables 2 and 3.

Friction force:

$$F_f = \mu \times W \qquad (18)$$

Friction torque:

$$T_f = \frac{1}{2\pi}\frac{F_f}{Pe} \qquad (19)$$

Total inertia:

$$J_t = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 + J_{ls} + J_m \qquad (20)$$

Example: A 200-lb load is positioned by a 44-in. long leadscrew with a 0.5-in. radius and a 5-rev/in. pitch. The reflected load inertia is:

$$J_l = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 = \frac{200}{386}\left(\frac{1}{2\pi 5}\right)^2$$
$$= 0.00052 \text{ lb-in.-sec}^2$$

Leadscrew inertia is based on the equation for inertia of a cylinder:

$$J_{ls} = \frac{\pi L \rho R^4}{2g} = \frac{\pi(44)0.28(0.5)^4}{2(386)}$$
$$= 0.00313 \text{ lb-in.-sec}^2$$

Total inertia to be connected to the motor shaft is:

$$J = J_l + J_{ls} = 0.00052 + 0.00313$$
$$= 0.00365 \text{ lb-in.-sec}^2$$

Motion control system

Once the mechanics of the application have been analyzed, and the friction and inertia of the load are known, the next step is to determine the torque levels required. Then, a motor can be sized to deliver the required torque and the control sized to power the motor. If friction and inertia are not properly determined, the motion control system will either take too long to position the load, or it will be unnecessarily costly.

In a basic motion-control system, Figure 7, the load represents the mechanics being positioned. The load is coupled or connected through one of the mechanical linkages previously described.

The motor may be a traditional PMDC servo motor, a vector motor, or a brushless servo motor. Motor starting, stopping and speed are dictated by the control unit which takes a low-level incoming command signal and amplifies it to a higher-power level for controlling the motor.

The programmable motion controller is the brain of the motion control system and controls the motor control (amplifier). The motion controller is programmed to accomplish a specific task for a given application. This controller reads a feedback signal to monitor the position of the load. By comparing a pre-programmed,

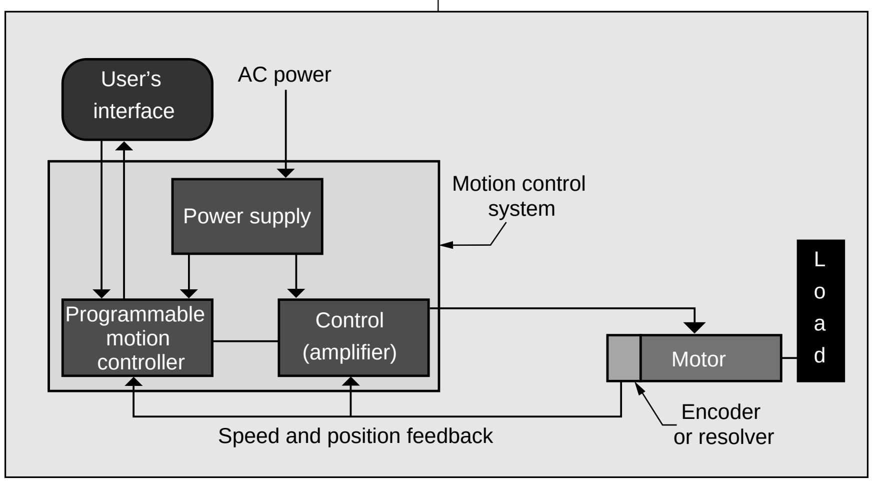


Figure 7 — Basic motion system.

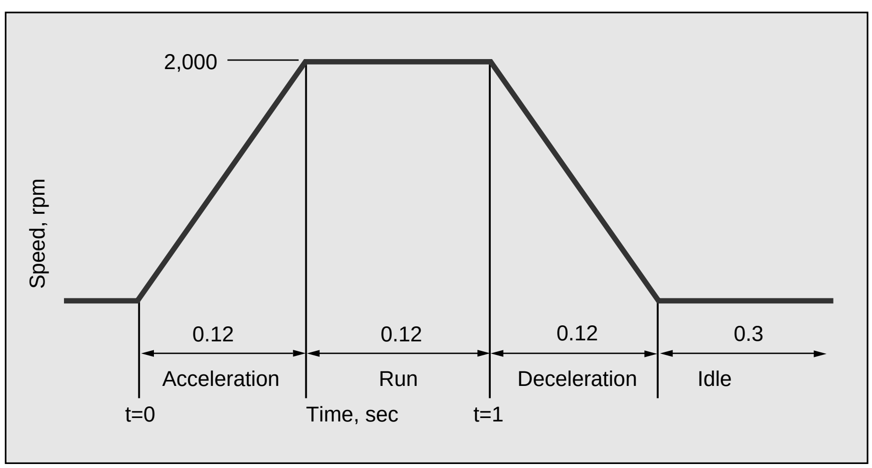


Figure 8 — Move profile.

"desired" position with the feedback position, the controller can take action to minimize an error between the actual and desired load positions.

Movement profile

A movement profile defines the desired acceleration rate, run time, speed, and deceleration rate of the load. For example, suppose with a system at rest (time =0, Figure 8), the motion controller issues a command to the motor (through the servo control) to start motion. At t=0, with full power-supply voltage and current applied, the motor has not yet started to move. At this instant, there is no feedback signal, but the error signal is large.

As friction and torque are overcome, the motor and load begin to accelerate. As the motor approaches the commanded speed, the error signal is reduced and, in turn, voltage applied to the motor is reduced. As the system stabilizes at running speed, only nominal power (voltage and current) are required to overcome friction and windage. At t=1, the load position approaches the desired position and begins to decelerate.

In applications with similar move profiles, most of the input energy is dissipated as heat. Therefore, in such systems, the motor's power dissipation capacity is the limiting factor. Thus, basic motor dynamics and power requirements must be determined to ensure adequate power capability for each motor.

Determining acceleration rate is the first step. For example, with a movement profile as shown in Figure 6, the acceleration rate can be determined from the speed and acceleration time. (Dividing the motor speed expressed in rpm by 9.55 converts the speed to radians per second).

$$\alpha_{acc} = \frac{S_m}{9.55 t_{acc}} \quad (21)$$

$$\alpha_{acc} = \frac{2{,}000}{9.55(0.12)} = 1{,}745.2 \text{ rad/sec}^2$$

Acceleration torque

The torque required to accelerate the load and overcome mechanical friction is:

$$T_{acc} = J_t(\alpha_{acc}) + T_f \quad (22)$$

$$= (J_t + J_{ls} + J_m)\alpha_{acc} + T_f \quad (23)$$

Example: Our application, Figure 9, requires moving a load through a leadscrew. The load parameters are:

Weight of load (W_{lb}) = 200 lb

Leadscrew inertia (J_{ls}) = 0.00313 lb-in-sec^2

Friction torque (T_f) = 0.95 lb-in.

Acceleration rate (α_{acc}) =1745.2 rad per sec^2.

Typical motor parameters are:

Motor rotor inertia (J_m) = 0.0037 lb-in.^{2}

Continuous stall torque (T_s) = 14.4 lb-in.

Torque constant (K_t) = 4.8 ;b-in./A

Motor resistance (R_m) = 4.5 Ω

Acceleration torque can be determined by substituting in equation 23.

$$T_{acc} = (.00052 + .00313 + .0037)1745.2 + .95$$

$$= 13.75 \text{ lb-in.}$$

Duty cycle torque

In addition to acceleration torque, the motor must be able to provide sufficient torque over the entire duty cycle or movement profile. This includes a certain amount of constant torque during the run phase, and a deceleration torque during the stopping phase.

Running torque is equal to friction torque (T_f), in this case, 0.95 lb-in.

During the stopping phase, deceleration torque is:

$$T_{dec} = -J_t(\alpha_{acc}) + T_f \quad (24)$$

$$= -(.00052 + .00313 + .0037)1{,}745.2 + .95$$

$$= -11.85 \text{ lb-in.}$$

Now, the root-mean-squared (rms) value of torque required over the movement profile can be calcuated:

$$T_{rms} = \sqrt{\frac{T_{acc}^2(t_{acc}) + T_{run}^2(t_{run}) + T_{dec}^2(t_{dec})}{t_{acc} + t_{run} + t_{dec} + t_{idle}}}$$

$$= \sqrt{\frac{(13.75)^2(.12) + (.95)^2(.12) + (11.85)^2(.12)}{.12 + .12 + .12 + .3}}$$

$$= 7.73 \text{ lb-in.}$$

The motor tentatively selected for this application can supply a continuous stall torque of 14.4 lb-in., which is adequate for the application.

Control requirements

Determining a suitable control (amplifier) is the next step. The control must be able to supply sufficient acceleration current (I_{acc}), as well as continuous current (I_{rms}) for the application's duty-cycle requirements.

Required acceleration current that must be supplied to the motor is:

$$I_{acc} = \frac{T_{acc}}{K_t} \quad (25)$$

$$= \frac{13.75}{4.8} = 2.86 \text{ A}$$

Current over the duty cycle, which the control must be able to supply to the motor, is:

$$I_{rms} = \frac{T_{rms}}{K_t} \quad (26)$$

$$= \frac{7.73}{4.8} = 1.61 \text{ A}$$

Power requirements

The control must supply sufficient power for both the acceleration portion of the movement profile, as well as for the duty-cycle requirements. The two aspects of power requirements include (1) power to move the load, (P_{del}) and (2) power losses dissipated in the motor, (P_{diss}).

Power delivered to move the load is:

$$P_{del} = \frac{T(S_m)(746)}{63{,}025} \quad (27)$$

Power dissipated in the motor is a function of the motor current. Thus, during acceleration, the value depends on the acceleration current (I_{acc}); and while running, it is a function on th rms current (I_{rms}). Therefore, the appropriate value is used in place of "I" in the following equation.

$$P_{diss} = I^2(R_m) \quad (28)$$

The sum of (P_{del}) and (P_{diss}) determine total power requirements.

Example: Power required during the acceleration portion of the movement profile can be obtained by substituting in equations 27 and 28:

$$P_{del} = \frac{13.75(2{,}000)}{63{,}025}(746) = 325.5 \text{ W}$$

$$P_{diss} = (2.86)^2(4.5)(1.5) = 55.2 \text{ W}$$

$$P_p = P_{del} + P_{diss}$$
$$= 325.5 + 55.2 = 380.7 \text{ W}$$

Note: The factor of 1.5 in the P_{diss} calculation is a factor used to make the motor's winding resistance "hot." This is a worst-case analysis, assuming the resistance is a 155 C.

Continous power required for the duty cycle is:

$$P_{del} = \frac{7.73(2{,}000)}{63.025}(746) = 182.9 \text{ W}$$
$$P_{diss} = (1.61)^2(4.5)(1.5) = 17.5 \text{ W}$$
$$P_p = 182.9 + 17.5 = 200.4 \text{ W}$$

In summary

The control selected must be capable of delivering (as a minimum) an acceleration (or peak) current of 2.86 A, and a continuous (or rms) current of 1.61 A. The power requirement calls for peak power of 380.7 W and continuous power of 200.4 W.

To aid in selecting both motors and controls (amplifiers), many suppliers offer computer software programs to perform the iterative calculations necessary to obtain the optimum motor and control.

From articles by Baldor Electric, published in the September 1995 and March 1996 issues of PTD.

COMPUTER TERMINOLOGY

Here are some of the vocabulary used in digital communication, whether it is between user and machine, machine and machine, or user and user. They are words used by those involved with PCs, PLCs, and control devices.

BBS — Bulletin board systems offer forums, mostly local or regional. They support all types of communication, conversation, and postings.

Bit — Symbolic representation of an "On" or "Off" state of a device. In computer code, it is indicated as a "1" or a "0."

Browsers — Graphics-based software programs that let you reach a variety of locations on the Internet and move from one to the other (surf). They also retrieve and display information, both text and graphics, from these locations. Examples include Netscape and Mosaic.

Bus — Years ago, bus referred to the path or paths data traveled on the backplane of a computer board. The definition is broadening to include data traveling within the physical medium of a few wires or cables.

Byte — Eight 1s or 0s grouped together, in any combination. Each group of eight bits represents an instruction, a command, or datum.

Chat channels — Addresses on the Internet where real time "conversations" take place between groups of individuals who are signed into a particular Chat Room. Usually they have a posted subject for discussion. Many times the same individuals return to the same room at the same time each day.

Connectivity — The ability to have one device connect, attach, or communicate with another.

Data highway — Another term for bus or network. Also, a network system created by Allen-Bradley.

Distributed — In communications, a configuration where control, command execution ability, or intelligence (such as microprocessor intelligence) is spread among two or more devices.

Domain or zone — Part of an Internet address. It consists of a two or three-letter designation for the type of organization or geographical location, such as:

.com	Commercial Organizations
.gov	Government Departments
.edu	Educational Institutions
.mil	Military
.net	Networking Units
.org	Professional Societies
.US	United States
.JP	Japan
.UK or .GB	United Kingdom
.DE	Germany

E-mail — Electronic mail supported across the Internet. Requires an address consisting of the Internet name or number of the recipient at the specific service provider. A CompuServe address has a series of numbers: 1111.1111@compuserve.com. No spaces are allowed between letters or numbers.

Fieldbus — A general term used to describe any bus that connects devices to microprocessor-based controls. Synonymous with device-level bus, sensor-actuator bus, mid-level bus.

File Transfer Protocol (FTP) — The means by which computer files and software programs are transferred from a host computer to recipient's computers.

Finger — Search capability for e-mail addresses where location is known but e-mail address is not.

Foundation fieldbus — A specification for process applications.

Gateway — Software on a board or chip that converts one communication protocol to another. Like converting a DOS program to an Apple-based program. Sometimes gateways also convert cable types.

Gopher — Menu-based system that helps find data residing on computers at various locations. Sometimes a long process down a series of decision-tree paths.

Hub — Hardware interface device between different cable types. Connects these cables together into a network.

Integration — Sufficient communication among devices, such that performance is enhanced to a level not possible as independent devices. Devices become part of a whole as opposed to separate pieces of a system.

Internet — Worldwide network of computers and computer networks. Begun by the Defense Department in 1969 to ensure communications between colleges and universities, contractors, and government. Colleges and students have used it for a long time, but companies and individuals jumped onboard only recently.

Kbaud — A transmission rate of one byte per second.

Network — All the cabling, wiring, and software parameters and control used to connect microprocessor-based devices over long distances. Distance is less of a factor now.

Packet — Several bytes of data grouped together in a network message.

Protocol — A specification that defines input signal levels, polarities, and speeds, and a device's output signals.

Search engines — Software programs that let the user find information sites by definition, subject, or even key words, then retrieve information from these sites, including text, graphics, and sound. Examples include Yahoo, Lycos, and Alta Vista.

Usenet — A worldwide bulletin board divided into categories on which you can post news, make inquiries, or add comments.

World Wide Web — A rapidly expanding group of home pages that provide information on many subjects; individuals, companies, organizations, and governments. Usually the address looks like: http://www.foggy.com/dognews/~csmith/collars.html. There are no spaces and every letter, number, and punctuation must be exact to reach the right address. Once there, the user can usually look at sub-pages or be linked with other locations of similar interest.

These definitions were taken from "PLCs bus into the future" (PTD July 1995 p. 19) and "Internet for Engineers" (PTD Aug. 1996, p. 59)

AMETEK®
TECHNICAL & INDUSTRIAL PRODUCTS

Pittman®
Servo Motor Application Notes

I. Basic Motor Operation

Permanent magnet, direct current servo motors convert electrical energy into mechanical energy through the interaction of two magnetic fields. One field is produced by a permanent magnet assembly; the other field is produced by an electrical current flowing in the motor windings. These two fields result in a torque which tends to rotate the rotor. As the rotor turns, the current in the windings is commutated to produce a continuous torque output.

Fig. 1 depicts a basic d-c motor model. The back emf, V, is an induced voltage produced by the relative motion between the permanent magnet field and the winding coils. The input voltage and current, E and I, represent the input power; the torque and speed, T and ω, represent the output power.

A simple circuit analysis of Fig. 1 yields the following basic motor equation:

Eq. (1) $E = I \times R_T + V + L \dfrac{dI}{dt}$ **(1)**

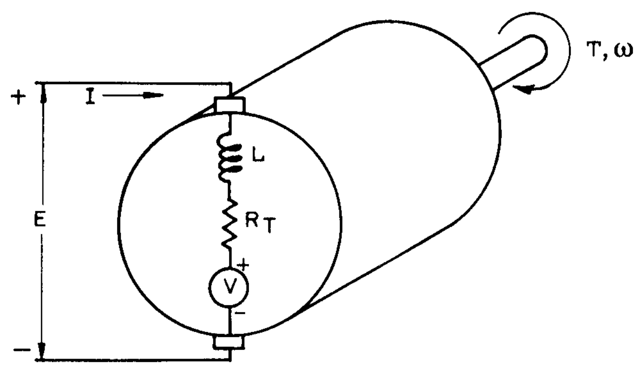


Fig. 1 Basic Motor Model

E =	applied voltage	V =	back emf voltage
I =	motor current	T =	output torque
L =	winding inductance	ω =	output speed
R_T =	resistance		

There are two important motor constants resulting from the coils of wire residing in the magnetic field produced by the magnets. The first is the motor back emf constant, K_E, which is a measure of the voltage per unit speed generated when the rotor is turning. The magnitude and polarity of K_E are functions of the shaft angular velocity, ω, and direction of rotation respectively. The back emf voltage can be expressed as the product of $K_E \times \omega$.

The second constant is the motor torque constant, K_T, which is a measure of the torque per unit current produced by the motor. In a permanent magnet d-c motor the torque is a linear function of the motor current. The torque produced by the motor is divided into two basic components: internal torque losses, T_M, and the external load torque, T_L. The motor current can be expressed as $(T_L + T_M)/K_T$.

In many applications where the motor electrical time constant is significantly less than the mechanical time constant, the $L \dfrac{dI}{dt}$ term in the basic motor equation, Eq. (1), can be assumed negligible. This is usually the case in iron-core motors such as those marketed by Pittman.

Incorporating the above characteristics into Eq. (1) yields the following form of the basic motor equation:

Eq. (2) $E = \left(\dfrac{T_L + T_M}{K_T} \times R_T\right) + \left(K_E \times \omega\right)$ **(2)**

When a step voltage is applied to a motor at rest there is an initial inrush current limited only by the circuit impedance since the back emf voltage is zero. This inrush current produces a large torque which begins to accelerate the motor and the connected load.

As the angular velocity increases, the back emf voltage increases and begins to limit the motor current. The steady state speed of the motor will be that speed at which the generated back emf voltage limits the current to a value that produces a torque equal to the sum of the load and internal motor torques $\left(\text{Current} = \dfrac{V}{R} = \dfrac{E - K_E \times \omega}{R_T} = \dfrac{T_L + T_M}{K_T}\right)$. Any changes in the applied voltage or the motor load will alter this balance and result in speed changes which tend to restore the balance.

II. Motor Performance Curves

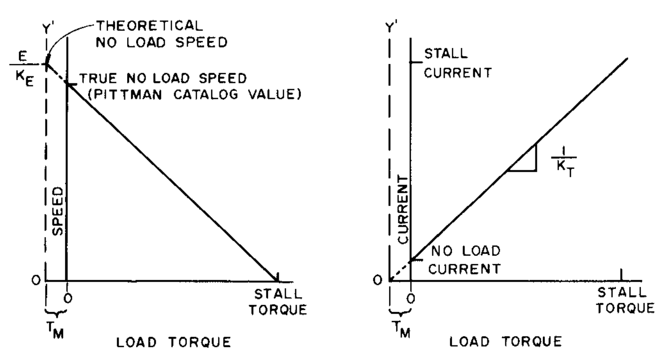
The most commonly used motor performance curves are speed, current, power, and efficiency all shown as functions of the load torque.

Both speed and current are linear functions of the load torque, T_L, as shown in Eq. (3) and Eq. (4). Both equations have the linear form y = mx + b with the load torque being the independent parameter, and the current and speed being the dependent parameters.

Eq. (3) Current: $I = \dfrac{1}{K_T} \times T_L + \dfrac{T_M}{K_T}$ **(3)**

Eq. (4) Speed: $\omega = \left(\dfrac{-R_T}{K_T \times K_E}\right) \times T_L + \left(\dfrac{E}{K_E} - \dfrac{R_T}{K_T \times K_E} \times T_M\right)$ **(4)**

Fig. 2 shows characteristic performance curves for both speed and current. The projections back to the y′ axes indicate the theoretical no load values in an ideal motor which has no internal torque losses. The construction of the curves is a simple process. The no load and stall points on both graphs are connected by a straight line. The motor will operate along this line as the load torque varies.



a) Speed vs. Torque **b) Current vs. Torque**

Fig. 2. Speed, Current vs. Load Torque

Eq. (4) also indicates that the speed of the motor is a function of the applied voltage. Both no load speed and stall torque are proportional to the applied voltage (assuming T_M is small). A motor can then be operated anywhere in the first quadrant of the speed-torque plane by varying the applied voltage. This is demonstrated in Fig. 3. Pittman catalog values for no load speed and stall torque are referenced to the nominal winding voltages listed in the catalog. The current vs. torque curve is independent of the applied voltage.

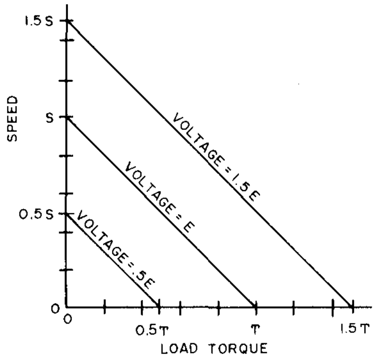
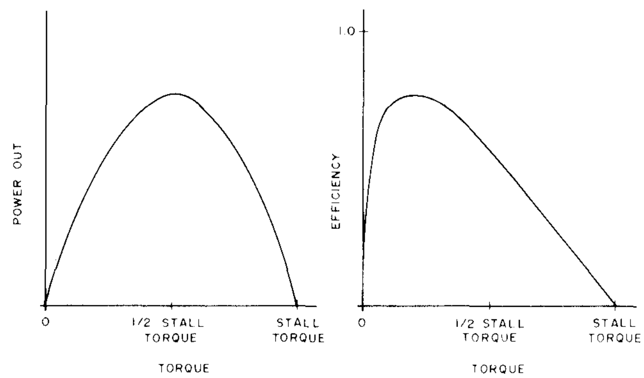


Fig. 3 Speed as a function of Voltage

Characteristic curves for power out and efficiency are shown in Fig. 4. Power out is the product of speed and torque. Input power is the product of the applied voltage and motor current. Efficiency is the ratio Power Out/Power In.



a) Power Out **b) Efficiency**

Fig.4 Power Out and Efficiency vs. Load Torque

III. Basic Motor Parametersand Tolerances

There are several fundamental motor parameters which define the motor's operating characteristics. These are listed below. The tolerances shown are standard manufacturing tolerances. Tighter tolerances for certain parameters are available upon request.

Parameter	Typical Symbols	Tolerance	Typical Units
Torque Constant	K_T, TPA	±15%	$\frac{oz \cdot in}{A}$ $\frac{N \cdot m}{A}$
Back emf Constant	K_E, BEF	±15%	$\frac{volts}{1000\ rpm}$, $\frac{volts}{rad/s}$
Terminal Resistance	R_T, RTR	±15%	ohms
Inductance	L, DUK	±10%	millihenries
Inertia	J, ERT	±10%	$oz \cdot in \cdot s^2$, $kg \cdot m^2$, $N \cdot m \cdot s^2$
Motor Torque losses	T_M	+30%	$oz \cdot in$, $N \cdot m$
Motor Friction	T_F, TOF	+50%	$oz \cdot in$, $N \cdot m$
No Load Current	I_O, INL	+30%	amperes

Pittman catalog values for terminal resistance are scaled from accumulated test data on a winding which is in the middle of the range of windings offered. This value also includes a typical brush resistance. Windings at the extremes of the range offered may not exactly conform to the scaled values (high voltage windings may have slightly lower resistance; low voltage windings may have slightly higher resistance). Contact your Pittman representative if exact values are required.

Motor torque losses are generally specified as static (breakaway) torques or dynamic (running) torques. Breakaway torque is a function of cogging (changes in magnetic circuit reluctance), brush friction, and bearing friction. These are affected by bearing type and preload, brush material and force, air gap flux density, and the magnetic circuit configuration. The Pittman catalog value for friction torque is a typical composite value. Maximum breakaway torque will depend on the motor configuration and may be 1.5 times the catalog motor friction value.

Dynamic torque losses are caused by magnetic hysteresis, eddy currents, windage, brush friction, and bearing losses. These are effected by motor speed, bearing type and preload, brush type and force, air gap flux densities, and the magnetic circuit materials.

These torque losses are generally expressed in terms of the motor no load current, INL ($INL = T_M/K_T$). The Pittman catalog value for no load current is a composite value. Maximum no load current may be 1.3 times the catalog value.

Several of the more commonly used derived motor parameters and their standard manufacturing tolerances are:

Parameter	Symbols	Tolerance	Derivation	Typical Units
Stall Torque	T_P, TPK	Reference	$\frac{E \times K_T}{R_T} - T_F$	oz·in, N·m
No Load Speed	So, SNL, ω_o, ωNL	±15%	$\frac{E - INL \times R_T}{K_E}$	rpm, rad/s
Stall Current	I_P, AMP	±15%	E/R_T	amperes
Motor Constant	K_M, PKO	Reference	$K_T/\sqrt{R_T}$	$\frac{oz \cdot in}{\sqrt{W}}$, $\frac{N \cdot m}{\sqrt{W}}$
Damping Constant (zero source impedance)	K_D, DPO	Reference	$\frac{K_T \times K_E}{R_T}$	oz·in/(rad/s), N·m/(rad/s)
Electrical Time Constant	τ_E, TCE	Reference	$\frac{L}{R_T}$	ms
Mechanical Time Constant	τ_M, TCM	Reference	$\frac{J \times R_T}{K_T \times K_E}$ $\frac{J}{K_D}$	ms

The motor damping constant and stall torque are functions of the total circuit impedance. When solid state drive circuits are used the dynamic resistance of the solid state devices must be included when determining damping and stall torque.

The Basic thermal parameters are:

Thermal Impedance	R_{TH}, TPR, θ_R	°C/W
Thermal Time Constant	τ_{TH}, TCT	min
Maximum Winding Temp.	TMX, θ_{MX}	°C

The Pittman catalog valves for R_{TH} and τ_{TH} are empirically derived with the rotor at stall, in free air, and without heat sinking. These conditions yield worst case values. Actual values will depend on the speed of rotation, heat sinking, and air flow over the motor.

IV. Motor Selection & Operating Considerations

Pittman® servo motors can be operated over a wide range of voltages, speeds, and loads. The major consideration in motor frame size selection is the rms load torque since the dominant portion of motor losses is usually the winding I^2R losses.

The first step in motor selection is to choose the motor type and frame size which is capable of producing the required load torque. In general the continuous torque capability of the various motor types and sizes can be calculated using Eq. (5).

Eq. (5): **(5)**

$$T_{CONT} = \sqrt{\frac{(155 - T_{amb})}{TPR} - \frac{T_M \times S}{C}} \times K \times PKO - T_M$$

where:

T_{CONT} = continuous load torque capability
155 = maximum winding temperature (155 °C)
T_{amb} = ambient temperature (°C)
TPR = motor thermal impedance (°C/W)
S = motor speed (rev/min)
C = 1352 for T_M = oz·in
9.549 for T_M = N·m
PKO = motor constant
T_M = motor friction torque
(The product of no load current and torque constant for any given winding.)
K = 0.71 for brush commutated, ferrite magnet motors
0.78 for brush commutated, rare earth magnet motors
0.79 for brushless, rare earth magnet motors
0.60 for brushless, ferrite magnet motors

Appendix A contains safe operating area curves derived using the above formula for most Pittman motor models.

After a frame size has been selected the proper winding needs to be specified. This is done by calculating the required torque constant for the selected frame size and specified load using Eq. (6).

Eq. (6): $$K_T = \frac{E}{\frac{T_L + T_M}{(PKO)^2} + \frac{S}{K}} \quad (6)$$

where:

K_T = required torque constant
E = supply voltage
T_L = load torque
T_M = motor friction
PKO = motor constant
S = load speed
K = 1352 for T_L = oz·in, S = rpm, PKO = oz·in/$\sqrt{W}$
9.549 for T_L = N·m, S = rpm, PKO = N·m/$\sqrt{W}$
1.000 for T_L = N·m, S = rad/s, PKO = N·m/$\sqrt{W}$

The winding with a torque constant closest to the value calculated by Eq. (6) is chosen. The catalog does not represent an exhaustive winding list. Consult your Pittman representative for assistance if needed. The winding choice can be checked by inserting the load values into Eq. (2) and verifying that the calculated required voltage is consistent with your supply voltage. Use the K_T, R_T, and K_E values for the winding you have chosen. WHEN PERFORMING THE ABOVE CALCULATIONS BE CERTAIN TO CONSISTENTLY USE UNITS WHICH RATIONALIZE.

When choosing a gearmotor the same procedure is followed using a load speed and torque translated back through the gearbox to the motor shaft as shown in equations (7) and (8). Gear ratios and efficiencies are listed in the Pittman gearmotor catalog.

Eq. (7) $$S_{Motor} = S_{Output} \times \text{Ratio} \quad (7)$$

E. (8) $$T_{Motor} = \frac{T_{Output}}{\text{Ratio} \times \text{Efficiency}} \quad (8)$$

A gear ratio should be chosen that will result in a translated motor speed and torque consistent with the motor's capability.

V. Thermal Considerations

Power losses in the motor are dissipated as heat which causes the motor temperature to rise. The thermal impedance (ultimate temperature rise per watt) is a measure of the winding temperature rise, relative to the ambient temperature, per watt of power dissipated in the armature.

Armature power dissipation can be closely estimated using Eq. (9).

Eq. (9): $$\text{Power Loss} = I^2 R_T + \frac{T_M \cdot \omega}{K} \quad (9)$$

where:

I = motor current
R_T = motor resistance
T_M = internal motor losses
ω = motor speed
k = rationalizing constant
= 1352 for T_M = oz·in, ω = rpm
= 141.6 for T_M = oz·in, ω = rad/s
= 9.549 for T_M = N·m, ω = rpm
= 1.000 for T_M = N·m, ω = rad/s

The armature temperature rise can then be calculated using the relationship in Eq. (10).

Eq. (10): $$\Delta T = \text{Power Loss} \times \text{TPR} \quad (10)$$

where: TPR = motor thermal impedance (deg/W)

Power Loss = value from Eq.(9)

The catalog value of thermal impedance is determined by the change in resistance method with the motor at stall, in free air, and without heat sinking. This yields a worst case value. Motor rotation, heat sinking, and air flow over the motor will improve the heat transfer and will result in a lower thermal impedance. The actual value of thermal impedance will depend on the characteristics of each application.

The motor resistance, torque constant, and back emf constant are functions of temperature. As the motor temperature increases each of the three parameters will change in a manner which degrades motor performance and increases the power losses. If a constant torque output is maintained the motor may reach a point of "thermal runaway" and burn out even if initial calculations showed an acceptable temperature rise (using values of R_T, K_T at ambient temperature).

A thermal runaway condition is usually encountered when the I^2R losses form a significant part of the total power losses. Fig. 5 shows the actual temperature rise as a function of the calculated temperature rise (using R_T, K_T at ambient) when a constant torque output is maintained in an application where the I^2R losses are dominant.

The actual resistance, torque constant, and back emf constant values for a given temperature change can be calculated using equations (11) and (12).

For Resistance

Eq. (11): $$R_2 = R_1 \times \frac{234.5 + T_2}{234.5 + T_1} \text{ (for copper wire)} \quad (11)$$

Actual Temperature Rise vs. Calculated Temperature Rise Given Constant Torque Output and Assuming I^2R Losses are Dominant

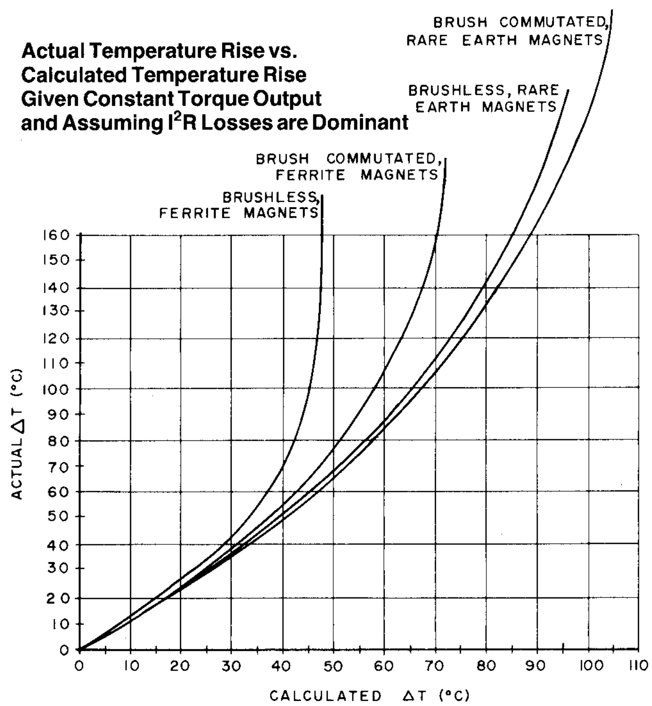


Fig. 5

For Torque/Back emf Constants

Eq. (12): $K_2 = K_1\ (1 + C[T_2 - T_1])$ **(12)**

where:

R_x = resistance at a given temperature
T_x = temperature (°C)
K_x = torque/back emf constants at a given temperature
C = −0.002 for ferrite magnets
= −0.00045 for rare earth magnets (PITMO® brush motors)
= −0.00025 for rare earth magnets (ELCOM® brushless motors)

The temperature rise of the magnet may be different from the calculated temperature rise in the winding. This must be considered when using Eq. (12). Empirical data for Pittman motors shows the following:

Eq. (13): $\Delta T \text{ magnet} = C \times \Delta T \text{ winding}$ **(13)**

where:

C = 0.5 for brush commutated, ferrite magnet motors
= 0.7 for brush commutated, rare earth magnet motors
= 1.0 for brushless motors

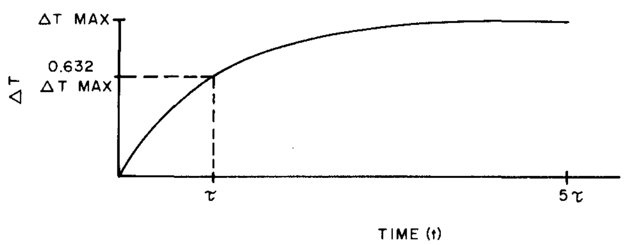


Fig. 6 Winding Temperature Rise As A Function Of Time.

Eq. (14): $\Delta T(t) = \Delta T_{max}\,(1 - e^{\frac{-t}{\tau}})$ **(14)**

where:

t = time   τ = thermal time constant

VI. Methods of Parameter Measurement

1. Terminal Resistance

A. Brush Commutated Motors

The resistance of brush commutated motors cannot be accurately measured with a conventional ohmmeter because the low voltage and current output of such devices will not break down the normal film which is present on the commutator surface. The resistance should be measured by locking the rotor shaft, applying a d-c voltage sufficient to drive a current of several hundred milliamps through the motor, and calculating R = E/I.

The values for several different shaft angular positions should be averaged to obtain the final result.

B. Brushless Motors

Brushless motor resistance can be measured with a conventional ohmmeter by probing at the proper coil termination points.

2. Back emf Constant

A. Brush Commutated Motors

Motor back emf is determined by measuring the d-c voltage generated at the motor terminals when the shaft is driven at a constant speed (generally 1000 – 3000 rpm).

$$\frac{\text{Volts}}{1000\text{ rpm}} = \frac{\text{Volts generated} \times 1000}{\text{rpm}}$$

$$\frac{\text{Volts}}{\text{rad/s}} = \frac{\text{Volts generated} \times 9.549}{\text{rpm}}$$

B. Brushless Motors

Since the Pittman ELCOM® series brushless motors generate a sinusoidal back emf voltage, the motor back emf constant must be derived from the measured voltage, and is a function of the motor winding configuration. Table 1 is a list of conversion constants for converting the generated voltage to the desired motor parameter.

The generated voltage should be measured at the indicated coil termination points with the motor disconnected from its drive circuit.

Table 1

Chart of Conversion Constants to Derive Torque Constant and Back EMF Constant from Generated Back EMF Voltage

		Derived Parameter			
		Torque Constant K_T		Back emf Constant K_E	
Generated Voltage		**oz·in/A**	**N·m/A**	**V/1000 rpm**	**V/(rad/s)**
4-Phase ELCOM®	$V_{p\text{-}p}$	$\frac{608.75}{\text{rpm}}$	$\frac{4.2987}{\text{rpm}}$	$\frac{450.16}{\text{rpm}}$	$\frac{0.45016}{\text{rad/s}}$
	V_{rms}	$\frac{1721.8}{\text{rpm}}$	$\frac{12.159}{\text{rpm}}$	$\frac{1273.2}{\text{rpm}}$	$\frac{1.2732}{\text{rad/s}}$
3-Phase Full Wave or 6-Phase ELCOM®	$V_{p\text{-}p}$	$\frac{645.67}{\text{rpm}}$	$\frac{4.5595}{\text{rpm}}$	$\frac{477.46}{\text{rpm}}$	$\frac{0.47746}{\text{rad/s}}$
	V_{rms}	$\frac{1826.2}{\text{rpm}}$	$\frac{12.896}{\text{rpm}}$	$\frac{1350.5}{\text{rpm}}$	$\frac{1.3505}{\text{rad/s}}$

To calculate the desired parameter multiply the generated voltage by the appropriate conversion constant listed in the chart.

3. **Torque Constant**
The torque constant is a measure of the torque per unit current produced by the motor. It can easily be determined by measuring the motor current and torque at two different points and calculating:

$$\text{Torque Constant} = K_T = \frac{T_2 - T_1}{I_2 - I_1}$$

The torque constant is also related to the back emf constant and can be determined by using the following relationships:

$$K_T\left(\frac{\text{oz}\cdot\text{in}}{\text{A}}\right) = \frac{\text{volts}}{1000\,\text{rpm}} \times 1.352 = \frac{\text{volts}}{\text{rad/s}} \times 141.6$$

$$K_T\left(\frac{\text{N}\cdot\text{m}}{\text{A}}\right) = \frac{\text{volts}}{1000\,\text{rpm}} \times 9.549 \times 10^{-3} = \frac{\text{volts}}{\text{rad/s}} \times 1.000$$

Table 1 also contains the conversion constants necessary to convert the brushless motor sinusoidal voltage measurements to the torque constant value.

4. **Starting Friction**
Starting friction is most accurately measured by using a constant current source to determine the maximum current required to establish continuous rotation and multiplying the result by the motor torque constant ($T = I \times K_T$). When measuring brushless motor starting friction the current supplied to the switching electronics (i.e. transistor base drive) must be subtracted from the measured current to obtain a correct result.

5. **Dynamic Friction**
Dynamic friction can be determined by multiplying the no load current and the torque constant at a given speed. Dynamic friction will contain a speed dependent component and a constant component. The switching electronics drive current for brushless motors should be subtracted as mentioned under STARTING FRICTION.

6. **Inductance**
The motor inductance is measured at 1 kH_Z with an inductance bridge by probing at the motor terminals or coil termination points. The values for several different shaft angular positions should be averaged to obtain the final result.

7. **Stall Torque**
The stall torque is determined by fitting a straight line through several speed and torque data points taken between no load and 3/4 stall. The x-intercept of the fitted line is the stall torque. Under certain conditions and with certain drive circuits the speed torque curve may deviate from a straight line and droop near the stall point producing a true stall torque less than the projected stall torque. This only needs to be considered if the motor is to be operated near its stall point. However, operation in the stall region is generally not recommended.

VII. Pitmo® Brush Commutated D-C Servo Motor Characteristics

1. Motor torque is a linear function of motor current.
2. Motor speed is a linear function of load torque when operated at a constant voltage.
3. The no load speed and stall torque are directly proportional to the applied voltage.
4. The motor direction of rotation is reversible by reversing the power supply polarity.
5. The motors are capable of operating over a wide range of voltage, speed, and torque.
6. Either ferrite or rare earth cobalt magnets are used. These magnets are not easily demagnetized and may be subjected to open circuit conditions, high current pulses, and plug reversing at rated voltage without suffering demagnetization.

VIII. ELCOM® Brushless D-C Servo Motor Characteristics

1. Motor torque is a linear function of motor current.
2. Motor speed is a linear function of load torque when operated at a constant voltage. (This may be affected in the stall region by drive electronics).
3. The no load speed and stall torque are directly proportional to the applied voltage. (This may be affected in the stall region by drive electronics).
4. The motor direction of rotation is reversible by a logic signal control of an H-bridge drive.
5. The motors are capable of being operated over a wide range of voltage, speed, and torque.
6. The motors exhibit extremely low friction and magnetic cogging.
7. The motors have very low thermal impedance and high power capability.
8. Long operational lifetimes are achieved since no brushes are used for current commutation. The limiting factor on motor life is the ball bearings in the motor.
9. Motor generated EMI is much less than that generated in brush commutated motors.

Application Examples

A. Continuous Duty, Single Point Load

1. The following operating conditions are defined:

Load Torque (T_L)	:	3 oz·in
Speed (S)	:	3000 rpm
Voltage (E)	:	12 VDC
Ambient Temp (T_{amb})	:	25 °C

2. A choice of the Model # 9433 frame size is made based on the continuous torque capability of that motor Eq. (5) (reference catalog Bulletin 9030, Motor Size Constants and Winding Constants for 9433, 9533).

   Motor Constant (catalog item 2), PKO = 2.66 oz·in/$\sqrt{\text{watt}}$
   Thermal Impedance (catalog item 14), TPR = 19.1 °C/W
   Motor Friction (catalog item 18 × item 22), T_M = 0.67 oz·in

   Rationalization Constant (see Eq. (5)), C = 1352
   Thermal Derating Factor (see Eq. (5)), K = 0.71

   The continuous torque capability of the Model 9433 motor is found by using Eq. (5) and the above data.

$$T_{CONT} = \sqrt{\frac{155 - T_{amb}}{TPR} - \frac{T_M \times S}{C}} \times PKO \times K - T_M$$

$$= \sqrt{\frac{155-25}{19.1} - \frac{0.67 \times 3000}{1352}} \times 2.66 \times 0.71 - 0.67$$

$$T_{CONT} = 3.7 \text{ oz·in}$$

Since the load torque (3 oz · in) is less than the continuous torque capability of the motor (3.7 oz · in) the choice is valid. Actually, the calculation of continuous torque capability is quite conservative since the thermal impedance (TPR) value used was the catalog worst case value. The same choice could have been made by using the safe operating area curves in Appendix A.

3. A winding choice is made by calculating the desired torque constant for the Model #9433 frame size using Eq. (6) and the above data.

$$K_T = \frac{E}{\frac{T_L + T_M}{PKO^2} + \frac{S}{K}} = \frac{12}{\frac{3+0.67}{2.66^2} + \frac{3000}{1352}}$$

$$K_T = 4.38 \text{ oz·in/A}$$

   Winding #2 is chosen because the torque constant for that winding (catalog item 18, K_T = 4.20 oz · in/A) is closest to the calculated value.

4. The motor choice is checked by calculating the required voltage for the given load using Eq. (2).

$$E = \frac{T_L + T_M}{K_T} \times R_T + K_E \times \omega$$

   T_M = motor losses = INL × K_T
   = 0.159 × 4.20 = 0.67 oz · in
   T_L = load torque = 3.0 oz · in
   K_T = torque constant = 4.20 oz · in/A
   R_T = terminal resistance = 2.48 ohms
   K_E = back emf constant
   $= 0.0297 \frac{V}{rad/s} = 3.11 \frac{V}{1000\,rpm}$
   ω = motor speed
   = 3000 rpm = 314.2 rad/s

$$E = \frac{3.0+0.67}{4.20} \times 2.48 + 3.11 \times \frac{3000}{1000} = 11.5 \text{ Volts}$$

This is consistent with the supply voltage of 12 VDC. The nominal motor current will be

$$I = \frac{T_L + T_M}{K_T}$$

$$I = \frac{3.0 + 0.67}{4.20} = 0.874 \text{ A}$$

5. Power and efficiency calculations.

   Power input = E × I = 12 × 0.874 = 10.5W

$$\text{Power output} = \frac{T \times S}{1352} = \frac{3 \times 3000}{1352} = 6.7\text{W}$$

$$\text{Efficiency} = \frac{P_{OUT}}{P_{IN}} = 6.7/10.5 = 0.64$$

6. Thermal Considerations
   Estimating the ultimate temperature rise of the winding can be an involved process. For example, when the continuous torque capability of the motor in this example was calculated the catalog value of thermal impedance (19.1 °C/W) was used. Depending on the application, the thermal impedance may be in the range of 9 to 19 °C/W. Also, the change in resistance and torque constant due to the temperature rise will increase the power losses in the motor.

   If an estimate of the ultimate temperature rise is needed the following procedure should yield an acceptable result. Refer to the previous motor parameters and operating conditions.

   a) Calculate the $T_M \times \omega$ power losses [last term in Eq. (9)].

$$P_{L_1} = \frac{T_M \times \omega}{K} = \frac{0.67 \times 3000}{1352} = 1.49\text{W}$$

   b) Calculate the temperature rise due to the above $T_M \times \omega$ losses using Eq. (10). For this example assume an actual thermal impedance of 14 °C/W.

   ΔT_1 = power loss × TPR = P_{L1} × TPR
   $\Delta T_1 = 1.49 \times 14 = 20.9$°C

   c) Calculate the resistance, R_T, and torque constant, K_T, values at ΔT, using Eq. (11), Eq. (12) and Eq. (13).

$$\text{Eq. (11)}: R_{T_1} = R_T \frac{234.5 + T_2}{234.5 + T_1} = \frac{2.48\,(234.5 + (25 + 20.9))}{234.5 + 25} = 2.68\Omega$$

$$\text{Eq. (13)}: \Delta T_{magnet} = C \times \Delta T_{wdg} = 0.5 \times 20.9 = 10.45\,°C$$

$$\text{Eq. (12)}: K_{T_1} = K_T(1 + C \times \Delta T_{mag}) = 4.20(1 - 0.002 \times 10.45) = 4.11 \text{ oz·in/A}$$

   d) Calculate the I^2R losses using R_{T_1} and K_{T_1} from step "c".

$$I^2R = \left(\frac{T_L + T_M}{K_{T_1}}\right)^2 \times R_{T_1} = \left(\frac{3+0.67}{4.11}\right)^2 \times 2.68 = 2.14\text{W}$$

   e) Calculate the temperature rise due to the I^2R losses.

$$\Delta T_2 = I^2R \times TPR = 2.14 \times 14 = 30\,°C$$

f) Use Fig. 5 to find the actual ΔT due to I^2R losses based on the value calculated in "e".

$$\Delta T_2 = 30°C$$

using Fig. 5, actual $\Delta T = \Delta T_3 = 37\,°C$

g) Find the estimated ultimate ΔT by adding ΔT_1, and ΔT_3.

$$\Delta T_{ult} = \Delta T_1 + \Delta T_3 = 20.9 + 37$$

$$\Delta T_{ult} = 57.9°C$$

The final values R_T, K_T, K_E, voltage, and current can now be calculated using Eq. (11) and Eq. (12).

$$R_{T_f} = 2.48 \times \left(\frac{234.5 + 25 + 57.9}{234.5 + 25}\right) = 3.03\Omega$$

$$K_{T_f} = 4.20 \times \left(1 - 0.002 \times \frac{57.9}{2}\right) = 3.96\ \text{oz}\cdot\text{in/A}$$

$$K_{E_f} = 3.11 \times \left(1 - 0.002 \times \frac{57.9}{2}\right) = 2.93\ \text{V/1000 rpm}$$

$$V = \frac{3 + 0.67}{3.96}\, 3.03 + \frac{2.93 \times 3000}{1000} = 11.6\ \text{Volts}$$

$$I = \frac{3 + 0.67}{3.96} = 0.93\text{A}$$

B. Incremental Motion Example

A certain application has the following characteristics and requirements:

Load friction torque (T_L)	$= 0.10$ N·m
Load inertia (J_L)	$= 40 \times 10^{-6}$ kg·m^2
Power supply (E)	= 24 VDC
Ambient temp (T_{amb})	= 25 °C

The load will be driven under closed loop control to obtain the following velocity profile:

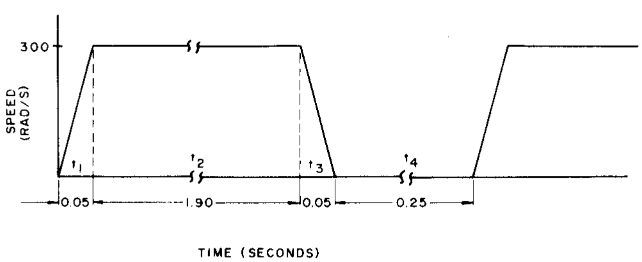


Fig. 7

Motor selection for incremental motion applications is not as straight forward as single point applications since the motor inertia must be known before calculating the rms torque. Experience would lead one to consider a motor in the 2-2⅛ inch diameter range for this example.

An initial selection of a Model #14203 is made.

Motor constant (PKO) $= 55.6 \times 10^{-3}$ N·m/$\sqrt{W}$
Motor inertia (J_M) $= 21.2 \times 10^{-6}$ kg·m^2
Motor friction (T_M) $= 10.9 \times 10^{-3}$ N·m
Thermal Impedance (TPR) = 8.1°C/W

T_M is found by taking the product of the torque constant and no load current for any winding.

1. The acceleration for periods t_1, t_3 is calculated.

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{300}{0.05} = 6000\ \text{rad/s}^2$$

2. The required torque for each time period is calculated.

a) Period t_1

Torque = (Inertia) (Accel) + Friction

$$T_1 = (J_L + J_M)\alpha + T_L + T_M$$

$$T_1 = (40 \times 10^{-6} + 21.2 \times 10^{-6}) \times 6000 + 0.10 + 10.9 \times 10^{-3}$$

$$T_1 = 0.478\ \text{N·m}$$

b) Period t_2

Torque = Friction

$$T_2 = (T_L + T_M) = 0.10 + 10.9 \times 10^{-3}$$

$$T_2 = 0.111\ \text{N·m}$$

c) Period t_3

Torque = Inertia (Accel) − Friction

$$T_3 = (J_L + J_M)\alpha - T_L - T_M$$

$$T_3 = (40 \times 10^{-6} + 21.2 \times 10^{-6}) \times 6000 - 0.10 - 10.9 \times 10^{-3}$$

$$T_3 = 0.256\ \text{N·m}$$

d) Period t_4

$$T_4 = 0$$

3. The rms torque is calculated.

$$T_{rms} = \sqrt{\frac{\Sigma(T_i^2 \times t_i)}{\Sigma(t_i)}}$$

where T_i = torque required for each period
t_i = time of each period

$$T_{rms} = \sqrt{\frac{(0.478)^2(0.05) + (0.111)^2(1.9) + (0.256)^2(0.05) + 0(0.25)}{0.05 + 1.9 + 0.05 + 0.25}}$$

$$T_{rms} = 0.130\ \text{N·m}$$

4. The required torque capability is checked against the continuous torque capability of the chosen motor Model #14203. For the speed in the $T_M \times \omega$ term use a weighted average of the speed during the cycle.

$$\omega_{avg} = \frac{\frac{300}{2}(0.05) + 300(1.9) + \frac{300}{2}(0.05)}{0.05 + 1.9 + 0.05 + 0.25} = 260\ \text{rad/s}$$

$$T_{cont} = \sqrt{\frac{155 - 25}{8.1}} - 10.9 \times 10^{-3} \times 260 \times 55.6 \times 10^{-3} \times 0.71$$

$$T_{cont} = 0.144\ \text{N·m}$$

This shows that the motor choice is valid. The motor losses were not subtracted from the T_{cont} value as shown in the last term of Eq.(5). This is because those losses were included in the rms torque calculations.

5. A winding is chosen based on the speed and load combination which will require the greatest voltage. This will occur at the end of period t_1 (speed = 300 rad/s, torque = 0.481 N·m). Eq.(6) is used.

$$K_T = \frac{E}{\frac{T_L + T_M}{PKO^2} + \frac{S}{K}} = \frac{24}{\frac{0.478 + 10.9 \times 10^{-3}}{(55.6 \times 10^{-3})^2} + \frac{300}{1}}$$

$$K_T = 52.4 \times 10^{-3}\ N \cdot m/A$$

Winding #2 is chosen since it has a torque constant closest to the calculated value.

$$K_T = 52.3 \times 10^{-3}\ N{\cdot}m/A$$

$$K_E = 52.3 \times 10^{-3}\ V/(rad/s)$$

$$R_T = 0.877\ Ohms$$

6. The required current and maximum voltage is calculated for each time period.

a) Period t_1

$$I = \frac{T_1}{K_T} = \frac{0.478}{52.3 \times 10^{-3}} = 9.1\ A$$

$$E = I \times R_T + K_E \times \omega = (9.1)(0.877) + (52.3 \times 10^{-3})(300)$$

$$E = 23.6\ V$$

b) Period t_2

$$I = \frac{T_2}{K_T} = \frac{0.111}{52.3 \times 10^{-3}} = 2.1\ A$$

$$E = I \times R_T + K_E \times \omega = (2.1)(0.877) + (52.3 \times 10^{-3})(300)$$

$$E = 17.5\ V$$

c) Period t_3

$$I = \frac{T_3}{K_T} = \frac{0.256}{52.3 \times 10^{-3}} = 4.9\ A$$

$$E = I \times R_T + K_E \times \omega = (4.9)(0.877) + (52.3 \times 10^{-3})(300)$$

$$E = 20.0\ V$$

The required voltages for each period are within the power supply capability of 24 VDC.

7. Thermal Calculations
The power dissipation and resulting temperature rise for an incremental motion example is much more involved than that of a constant load example. If a motor is chosen consistent with the rms torque requirements, then the temperature rise should not present a problem. The general procedure in example A can be used to calculate the temperature rise if the various power dissipation components are calculated for each cycle and time weighted averages of the components are used to obtain the final result.

C. ELCOM® Brushless Motor Application Example

Choosing a Pittman ELCOM® brushless motor for an application is very similar to the process followed in choosing a brush commutated motor. Although the brushless motor catalog does not list No Load Speed, Stall Torque, and Rated Voltage values, note that these parameters were not used in selecting a brush commutated motor. All the basic motor parameters necessary to properly select a brushless motor are included in the catalog specifications.

1. Assume the following requirements are given for an application for which a brushless motor is desired:

Load Speed	= 500 rad/s
	= (0.5 krad/s)
Load Torque	= 300 mN·m
	= (0.300 N·m)
Supply Voltage	= 70 Volts

A 0.03 m^2 (300 cm^2) heat sink is provided.

A Pittman Darlington transistor H-bridge drive board will be used to drive the motor.

2. A quick selection of the motor frame size can be made by referring to the Safe Operating Area curves in the motor data sheets. The 3100 and 4100 frame sizes can quickly be eliminated because the 300 mN·m torque load is well beyond the specified operating range of those motors (refer to Appendix A). The 5100 frame size Safe Operating Area Curve indicates that the Model 5113 can safely operate at 300 mN·m, 500 rad/s if a heat sink of at least 0.025 m^2 is provided. This requirement is met since the application specified a 0.03 m^2 heat sink. Actually, mounting the motor to any sizeable metal surface would have provided the minimum required heat sink area.

3. The next step is to choose an appropriate winding within the desired 5113 frame size. A slight modification has to be made to the equation used for winding selection (Eq. (6), Pg. 4) to compensate for the voltage drop across the solid state electronic drive devices. The corrected equation to calculate the motor torque constant is:

$$K_T = \frac{E - V_D}{\frac{T_L + T_M}{(K_M)^2} + \frac{S}{K}}$$

Where:

K_T	= required motor torque constant
E	= supply voltage
V_D	= transistor or MOSFET voltage drop
T_L	= load torque
T_M	= motor friction torque
K_M	= motor constant
S	= load speed
K	= rationalization constant
	= 1352 for oz·in, rpm units,
	= 9.549 for N·m, rpm units,
	= 1.000 for N·m, rad/s units.

The voltage drop, V_D, is determined by the application and the type of solid state devices used. Typical values for Pittman H-Bridge drive boards are:

Darlington Transistor, V_D = 5.0 v.
MOSFET Transistor, V_D = 1.0 v

Motor friction torque, T_M, is a combination of the static and dynamic torque losses in the motor. For brushless motors T_M is the sum of the friction torque, T_F (Item 7 in the catalog), and the viscous losses.

Friction Torq = T_F (Catalog Item 7)

Viscous losses = D_F (Catalog Item 6) × motor speed.

For this example the motor friction torque would be:

$$T_M = 4.0 \times 10^{-3} + (17 \times 10^{-6})(500 \text{ rad/s})$$

$$T_M = 12.5 \times 10^{-3} \text{ N·m}$$

(ref. Bulletin 5000, Items 6, 7 for Model 5113)

The motor constant is listed in the motor catalog as Item 2. For the ELCOM® Model 5113 the motor constant is 53.2×10^{-3} N·m/$\sqrt{W}$.

The rationalization constant, K, will be 1.0 in this example because the units used are N·m and rad/s.

The appropriate winding torque constant is chosen by filling these values into the above equation.

$$K_T = \cfrac{70 - 5}{\cfrac{0.300 + 12.5 \times 10^{-3}}{(53.2 \times 10^{-3})^2} + \cfrac{500}{1}}$$

$$K_T = 106 \times 10^{-3} \text{ N·m/A}$$

Winding 60T28 of Model 5113 has a torque constant of 104×10^{-3} N·m/A and should be chosen for this application since it most nearly matches the calculated value.

4. Check the motor choice and the required current

The current required is calculated by dividing the load and motor friction torques by the torque constant.

$$I = \frac{T_L + T_M}{K_T} = \frac{0.300 + 12.5 \times 10^{-3}}{104 \times 10^{-3}}$$

$$I = 3.0 \text{ A}$$

The required voltage is checked using Eq. (2), pg. 1, and adding the voltage drop V_D. The $T_L + T_M/K_T$ term is the current which was calculated above. The resistance, R, and the back EMF constant, K_E, are obtained from the catalog (Items 17 and 16 respectively for 5113 60t28). ω is the motor speed

$$E = I \times R + K_E \times \omega + V_D$$

$$= 3.0 \times 3.83 + (104 \times 10^{-3}) \times 500 + 5.0$$

$$E = 68.5 \text{ v}$$

This compares favorably with the 70v supply specified

Selecting a Brush-Commutated DC Motor

BASIC PARAMETERS

Permanent magnet direct current (DC) motors convert electrical energy into mechanical energy through the interaction of two magnetic fields. One field is produced by a permanent magnet assembly; the other field is produced by an electrical current flowing in the motor windings. The relationship between these two fields results in a torque that tends to rotate the rotor. As the rotor turns, the current in the windings is commutated, or switched, to produce a continuous torque output.

Brush DC motors can be operated over a wide range of voltages, speeds, and loads. Output power for a brush DC motor is a product of speed and torque; input power is a product of the applied voltage and motor current.

The first step in motor selection is to decide if you are going to need a gearbox or not. This will typically depend on your maximum required load speed. A good rule of thumb might be to use a gearmotor if your maximum speeds will be below 1000 RPM, and use only a motor if your maximum speeds will be above 1000 RPM.

If you are going to use a gearbox, start by selecting one that meets the torque requirements of your application. Gearboxes are usually rated by their maximum allowable output (load) torque. Once you have chosen a gearbox type, the appropriate ratio must be selected. Determine the ratio by dividing the maximum acceptable input speed to the gearbox by the maximum desired output (load) speed, then choosing the closest available ratio. Acceptable gearbox input speeds vary, but are typically on the order of 6000 RPM. Calculate the motor speed and torque requirements using the following equations:

WM = WL x N and TM = TL / (N x n)

where WM = Motor Output Speed

WL = Load Speed

N = Gear Ratio

TM = Motor Output Torque

TL = Load Torque

n = Gearbox Efficiency

Once the motor requirements have been determined, choose a motor type and frame size capable of producing the required motor torque. For continuous operation, select a motor with a continuous torque rating greater than that of the required torque.For intermittent operation with a sufficiently short on-time, select a motor with a continuous torque greater than that of the rms value of the required torque.

Motor manufacturers will provide continuous torque ratings for their motors under certain operating conditions, including a specified ambient temperature (often 25 degrees C. or 40 degrees C.) and thermal resistance (dependent on whether a heat sink is utilized.) Take care to read the fine print when comparing continuous torque ratings as they may need to be adjusted if these assumptions do not match your actual operating conditions.

After a frame size has been selected, the proper winding needs to be specified. Generally, voltage and torque will be known values, and speed and current will need to be determined. The best winding choice will be that which comes closest to providing the desired speed and current draw given the supply voltage and load torque. The governing motor equations to determine speed and current follow:

$W = (VS - I \times Rmt) / KE$ and $I = TL / KT + INL$

where W = Speed

VS = Supply Voltage

I = Current

Rmt = Motor Terminal Resistance

KE = Back-EMF Constant

T = Load Torque

KT = Torque Constant

INL = No-Load Current

While these equations are suitable for most applications, it is important to realize that they are only the basic formula and do not take into account thermal considerations. Motor heating will alter some of the parameters in these calculations, including resistance, torque constant, and back-emf constant. Accounting for these effects adds significantly more complexity to the process. Finally, when going through any calculations, make sure to maintain consistency among units of measure.

COMPONENT FEATURES

"Off-the-shelf" brush-commutated DC motors are the exception, rather than the rule, and they are frequently customized to meet specific design and performance criteria for an application. Among those components typically specified:

•Optical Encoders: Since closed loop servo applications require velocity and/or position feedback, common motor options include incremental optical encoders, which supply accurate position, velocity, acceleration, and direction feedback for precision motion control. Encoders can be added to any motor or gearmotor with wires or side-exiting power terminals and can be metal-housed or open air. They can be factory-mounted or prepared for mounting in the final stages of end-product assembly. Encoders are usually specified with either two- or three-channel, TTL-compatible quadrature outputs. The maximum frequency, which limits the maximum operational speed, is typically 100 KHz. In a three-channel unit, the third channel provides an index signal or pulse once per revolution of the codewheel.

Another encoder option, the rotary pulse indicator (RPI), is a single-channel unit with open-collector or TTL-compatible outputs. RPIs are low-cost solutions for appliance applications that need 120 counts per revolution or less without direction-sensing capabilities.

•***Shafts:*** The shaft of any motor can be customized with a flat, journal, cross hole, keyway, slot, groove, gear, or pulley. These options can be combined to meet application requirements. As examples, a cross hole can allow a pulley to be pinned to the shaft, or a journal can include a groove. A variety of other combinations are possible. Shaft material can be customized from the standard 416 Stainless steel to other grades, such as 303 and 316 Stainless with different Hardness ratings. Standard and common optional shaft diameters include a variety of sizes from 4mm to 8 mm and from 5/32-inch to 3/8-inch.

•***Gearheads:*** Gearheads increase output torque and decrease speed. These functions and their efficiency vary with different models and applications. For most applications a spur gearhead is flexible enough to meet specific torque, noise, and cost requirements. Standard spur gearheads feature sintered nickel-steel gears, which provide moderate power handling with average audible noise. The sintering process allows for close tolerances (AGMA Q7-8) at a low cost. The sintered gear functions as a lubrication holder and helps dampen sound. When more strength is required, a hybrid cluster (an assembly of a cut-steel pinion and a sintered gear) or precision-cut steel gears can be chosen. Other gearhead options include planetary gearheads for lower backlash and much higher torque or Delrin (moldable polymer) gears that produce less noise than sintered gears.

•***Wire and Cable Assemblies:*** Custom wire and cable assembly options are designed to speed motor installation and boost component reliability. Almost any connector style and wire type can be specified for motors, gearmotors, and encoders.

•***EMI/RFI Suppression Components:*** A number of cast and stamped component solutions have been developed to reduce the amount of electrical noise generated by a motor. For low-frequency RFI (typically below 30 MHz) capacitors are generally effective, and there is an inverse relationship between the value of the capacitor and the attenuated noise frequency. Capacitors installed by the motor manufacturer enable strategic placement inside the motor frame for optimum filtering as close to the noise source as possible. For high-frequency noise (generally above 30 MHz) ferrite beads can help reduce RFI. A combination of ferrite beads and capacitors provides the most effective suppression by creating a low-pass LC filter that is inductive-capacitive at low frequencies and dissipative at high frequencies.

Mounting for each component may vary from slipping ferrite beads over wires to soldering chokes near the motor terminals, depending on the best solution for the application.

•***Brakes:*** Developed as a safety and energy-saving feature, rear-mounted power-off and power-on electro-magnetic brakes prevent a motor or gearmotor from rotating freely. Brakes typically are offered for 16 and 40 oz-in static torques and 12, 24, 28, 48, and 90 VDC operation, although other voltages, including 120 VAC, are available.

A power-off brake stops a motor when power is removed and releases the motor when power is reapplied. In low-duty applications, the brake saves energy by maintaining a known motor position without power. An added safety feature is that should power be lost while the motor is lifting an object by pulley or lead screw, the brake will lock the motor and prevent the object from falling. A power-on brake holds the motor in place upon application of power and releases the motor when power is removed.

DEALING WITH EXTREMES

When brush-commutated DC motors are used to drive gears or pulleys, avoid excessive side loads. These can push a motor to an extreme and lead to motor failure. If side loads will be present, ball bearings are usually recommended. Environmental conditions will impact, too, on effective brush DC motor operation and performance. For example, the moisture in the air acts as a lubricant and, where humidity is low, the resulting lower lubrication will accelerate brush wear and shorten motor life. (Special brushes are designed to solve this problem.)

AVOIDING PITFALLS

•Know the proper rating of the motor for an application and recognize and understand the importance of continuous operation vs. duty cycle.
•Do not press fit components on a motor's shaft (in any direction) without proper support at the other end of the shaft. This action could lead to motor failure.
•Do not apply adhesives or other foreign material directly to shafts that could contaminate the bearings. These could negatively affect performance. If such materials are to be applied, it is generally advised to apply them to the component to be secured to the shaft to reduce the chance of contamination.
•Consult with your motor manufacturer before, during, and after a motor is specified for an application.

STANDARDS AND REGULATIONS

NEMA publications represent the most relevant sources for standards relating to traditional motor products and devices. Other standards include ANSI and IEC for rotating machinery, as well as IEEE standards for motor-related test procedures. A "CE" designation assures compliance with appropriate standards for those products used in the European marketplace. In addition to product standards, a set of quality-oriented standards applies to motor suppliers. Those manufacturers that have achieved ISO certification demonstrate documented adherence to procedures and operations consistent with international quality standards.

MOTOR FAILURE MODES

The primary cause for failure of brush-commutated DC motors over time is ongoing brush wear. The traditional method for mounting copper or silver graphite brushes in motor assemblies has been to solder the brushes onto standard cantilever springs to enable the required constant contact with the commutator. This conventional spring design, however, carries inherent drawbacks as force levels diminish over time, and motor failure can result.

The problem can be overcome by housing the brushes within a specially designed cartridge and utilizing torsion springs to ensure desired even force over the life of a motor. The cartridge, which fits into the motor base, consists of a two-piece, high-temperature plastic snap-together assembly in which each of two brushes is seated securely within its own specially constructed slot. This design effectively restricts the brushes to traveling in a track in a desired linear motion.

The cartridge design further provides for an ideal region of pressure (6-8 lbs. psi) for the brushes to withstand the detrimental effects of mechanical wear. Other typical causes that can result in motor failure include motor overloading, contamination of the armature, and electrical or mechanical malfunctions. There are many others, depending on motor design, operating parameters, and in-use service and safeguards.

COST SAVINGS

Users can save money (and headaches) at the outset by partnering with a quality motor manufacturer from the very beginnings of the design stage. This will minimize (and likely eliminate) costly mistakes and ensure that a motor performs as intended and required in an application.

This early involvement also can open a window to available motor features and options, which could help initially to reduce labor and material-handling costs for the customer and provide for easier motor installation.

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Spur vs. Planetary Gearheads For Motors

Gearheads can be integrated into any DC motor design and the selected gear type will play a key role in determining characteristics such as backlash, efficiency, maximum torque output, and reduction ratios.

A gearhead (or gear reducer) converts the rotary motion of a motor by increasing the torque output and decreasing the rotational speed by a specified ratio. Two standard gearing systems are spur gearheads and planetary gearheads. Each type of gearhead can be modified with different output shafts and bearing configurations to achieve torque, noise, and cost requirements.

In general, **spur gearheads** are relatively simple and inexpensive and will suit most needs in relatively low-torque applications. However, while they are less expensive and generally quieter than planetary gearheads, spur configurations can have higher backlash at lower torque ratings and are usually less efficient than planetary types of similar construction. For constant velocity and undirectional applications where backlash is less of a concern, spur gearheads are ideal.

A spur gearhead, in its simplest form, features a toothed gear coupled to the input shaft and another to the output shaft. (Stages can further be stacked to achieve increased ratios.) Typical backlash is 20 arc minutes.

The direction of rotation for spur gearheads compared to motor output shaft direction will change depending on the number of "gear passes." (No change in direction in an even number of "passes" and a reverse change in direction for an odd number.)

Planetary gearheads are generally specified for high-torque applications due to their design featuring multiple rotating gears that increase torque load-carrying capability. Planetary gearheads tend to be more robust with higher accuracy and lower backlash than spur gearheads. They are well-suited for higher-load applications in small packages ranging from nut runners and nut setters to small medical tools, pumps, and other devices.

These geartrains derive their name from a design resemblance to a solar system with "planet" gears revolving around a "sun" gear. The input shaft rotates the sun gear and each of the planet gears simultaneously supplies a torque to the rotating carrier plate, which then supplies a torque to the output shaft.

Efficiency Considerations

Spur gearheads with a single gear pass or stage can reach 90% efficiency and can achieve a reduction ratio of 6:1, which can be increased by increasing the number of stages. However, more stages will result in more losses to the system due to added friction loads, therefore reducing the gearhead's efficiency. A single-stage planetary gearhead is usually over 90% efficient with a backlash as low as 5 arc minutes.

Efficiency should always be a consideration in selecting an appropriate gearhead configuration for an appliance application. As an example, a 10:1 ratio gearbox reduces the input speed from the motor to the gearbox by a factor of 10. The torque for this same gearbox can be expressed as

T (gearbox output) = T (motor) x ratio (10) x Efficiency

Recommended Materials

Sintered nickel-steel is the usual standard material for most geartrains because the powdered metal process allows for close tolerances and the porosity of these gears helps the gear hold lubricant while reducing audible noise. However, where higher torque or more strength is needed, cut steel or hybrid cluster material is recommended.

The Basics of Optical Encoders

Closed loop servo applications for brush commutated and brushless DC motors and gearmotors require positioning feedback from which crucial velocity and acceleration data are derived. With accurate feedback comes an opportunity for enhanced motor control and an even wider range of applications. One method to generate reliable position feedback is with two- or three-channel optical incremental encoders. In addition, DC motor and encoder combinations can be customized with differential line drivers to counter the effects of electrically noisy environments and to ensure uncorrupted positioning feedback from the encoder to the control circuit. This is especially important, because even one false signal adding to or subtracting from the position count has the potential to degrade the accuracy of the DC servo system.

Each TTL compatible optical incremental encoder typically contains a lensed Light Emitting Diode (LED) source, an integrated circuit (IC) with detectors and output circuitry, and a codewheel that rotates between the emitter and detector IC. In two-channel encoders, the outputs are two square waves in quadrature; three-channel encoders offer a third index channel output in addition to the two-channel quadrature. This third index channel is generated once for each full rotation of the codewheel and thus offers an ideal point of reference. For codewheels 2 in. or less in diameter, resolution generally can be specified up to 2048 counts per revolution (CPR).

Optical incremental encoders essentially translate the rotary motion of a shaft into either a two- or a three-channel digital output. The light from the LED source is collimated into a parallel beam by means of a single polycarbonate lens located directly over the LED. Opposite the emitter is an integrated detector circuit. This IC consists of multiple sets of photodetectors and the signal processing circuitry necessary to produce the digital waveforms.

Either a metal or film codewheel is employed to rotate between the emitter and detector, causing the light beam to be interrupted by the pattern of spaces and bars on the codewheel. The photodiodes that detect these interruptions are arranged in a pattern that corresponds to the radius and design of the codewheel. These detectors are also spaced such that a light period on one pair of detectors corresponds to a dark period on the adjacent pair of detectors. The photodiode outputs are then fed through the signal processing circuitry. Comparators receive these signals and produce the final outputs for the channels. Due to the integrated phasing technique, the digital output of one channel is in quadrature with that of the other (90 degrees out of phase).

In a three-channel encoder, the output of the comparator for the third channel is sent to the index processing circuitry along with the outputs of the other two channels. The final output of the third channel (generated once for each full rotation of the codewheel) can be gated to be coincident with the low states of the first two channels. The result is highly accurate signal feedback and reliable point of reference.

Encoders are designed to be mounted quickly and easily to a motor and will provide reliable motion detection in high-volume applications, including printers, plotters, tape drives, positioning tables, and industrial and factory automation equipment. As an alternative low cost solution for applications that need velocity feedback only, an option is a Rotary Pulse Indicator (RPI). This is a single-channel encoder with open collector or TTL compatible outputs and, because this is a single-channel device, direction information is not generated.

In encoder applications where a reduction in the effects of conducted and radiated noise is desired, the assembly can be customized with a differential line driver, which will enable improved signal integrity.

Differential circuits improve noise immunity by processing a signal that is the algebraic difference of two complementary signals at the input. The differential line driver receives the signal from the encoder and inverts polarity on one output to form complementary signals. A 5V input signal would transmit as 5V on one output and 0V on the other. Because the transmission lines are balanced and positioned closely, any noise induced in the circuit equally affects the signal amplitude, polarity, and phase in both wires.

The lines feed to a differential receiver, which re-inverts one input and adds the voltage in the lines, effectively canceling electromagnetic interference (EMI). Therefore, if a +1V noise spike enters the 5V system, the lines would carry 6V and 1V for the duration of the spike, then the receiver would invert the 1V input and detect the original 5V.

To ensure that noise equally affects both transmission lines, differential circuits commonly employ twisted-pair wiring, especially as transmission distances become longer. For shorter transmissions, ribbon cable suffices. With twisted-pair wiring, designers can achieve higher noise immunity, because the inductively coupled noise currents are out-of-phase and effectively cancel one another in each loop. Wires should be terminated at the receiver end only with a resistor equal to the differential line impedance.

In addition to reducing common-mode noise, the differential circuit also supports longer transmission distances by providing better noise margins and boosting signal output. Typically, optical incremental encoders only provide source current in the microamp range. Standard differential line drivers, however, provide up to 20 milliamps of drive current, which is five times more sinking current than average encoders. Designers can determine acceptable line length by examining the signal strength at the end of the line and the amplification possible with the receiver.