

Engineering Reference

Sizing and Selection of Exlar Linear and Rotary Actuators

Move Profiles

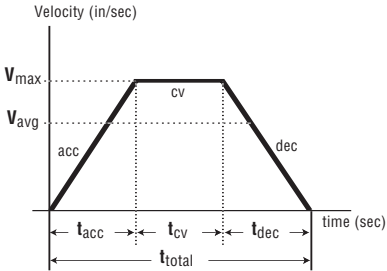
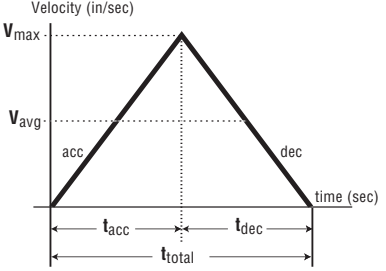
The first step in analyzing a motion control application and selecting an actuator is to determine the required move profile. This move profile is based on the distance to be traveled and the amount of time available in

which to make that move. The calculations below can help you determine your move profile.

Each motion device will have a maximum speed that it can achieve for each specific load capacity. This maximum speed will determine which type of motion profile can be used to complete the move. Two common types of move profiles are trapezoidal and triangular.

If the average velocity of the profile, is less than half the max. velocity of the actuator, then triangular

profiles can be used. Triangular Profiles result in the lowest possible acceleration and deceleration. Otherwise a trapezoidal profile can be used. The trapezoidal profile below with 3 equal divisions will result in 25% lower maximum speed and 12.5% higher acceleration and deceleration. This is commonly called a 1/3 trapezoidal profile.

<p>Linear Move Profile Calculations</p> <p>V_{max} = max.velocity-in/sec (m/sec) V_{avg} = avg. velocity-in/sec (m/sec) t_{acc} = acceleration time (sec) t_{dec} = deceleration time (sec) t_{cv} = constant velocity (sec) t_{total} = total move time (sec) acc = accel-in/sec² (m/sec²) dec = decel-in/sec² (m/sec²) cv = constant vel.-in/sec (m/sec) D = total move distance-in (m) or revolutions (rotary)</p>	<p>Trapezoidal Move Profile</p> 	<p>Triangular Move Profile</p> 
<p>Standard Equations</p> <p>$V_{avg} = D / t_{total}$ If $t_{acc} = t_{dec}$ Then: $V_{max} = (t_{total} / (t_{total} - t_{acc})) (V_{avg})$ and $D = \text{Area under profile curve}$ $D = (\frac{1}{2}(t_{acc} + t_{dec}) + t_{cv})(V_{max})$</p>	<p>Trapezoidal Equations</p> <p>If $t_{acc} = t_{cv} = t_{dec}$ Then: $V_{max} = 1.5(V_{avg})$ $D = (\frac{2}{3})(t_{total})(V_{max})$ $acc = dec = \frac{V_{max}}{t_{acc}}$</p>	<p>Triangular Equations</p> <p>If $t_{acc} = t_{dec} = t_{total}/2$ Then: $V_{max} = 2.0(V_{avg})$ $D = (\frac{1}{2})(t_{total})(V_{max})$ $acc = dec = \frac{V_{max}}{t_{acc}}$</p>

The following pages give the required formulas that allow you to select the proper Exlar linear or rotary actuator for your application.

The first calculation explanation is for determining the required thrust in a linear application. The second provides the necessary equations

for determining the torque required from a linear or rotary application. For rotary applications this includes the use of reductions through belts or gears, and for linear applications, through screws.

Pages are included to allow you to enter your data and easily perform the required calculations. You can

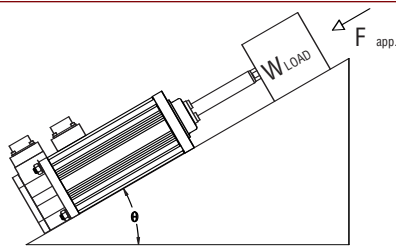
also describe your application graphically and fax it to Exlar for sizing. Reference tables for common unit conversions and motion system constants are included at the end of the section.

Sizing and Selection of Exlar Linear Actuators

Thrust Calculations

Definition of thrust:

The thrust necessary to perform a specific move profile is equal to the sum of four components of force. These are the force due to acceleration of the mass, gravity, friction and applied forces such as cutting and pressing forces and overcoming spring forces.



Terms and (units)

THRUST = Total linear force-lbf (N)	\emptyset = Angle of inclination (deg)
F_{friction} = Force from friction-lbf (N)	t_{acc} = Acceleration time (sec)
F_{acc} = Acceleration force-lbf (N)	v = Change in velocity-in/sec (m/s)
F_{gravity} = Force due to gravity-lbf (N)	μ = Coefficient of sliding friction
F_{applied} = Applied forces-lbf (N)	(refer to table on page 136 for different materials)
W_L = Weight of Load-lbm (kg)	g = 386.4: Acceleration of gravity - in / sec ² (9.8 m/ sec ²)

Thrust Calculation Equations

$$\text{THRUST} = F_{\text{friction}} + [F_{\text{acceleration}}] + F_{\text{gravity}} + F_{\text{applied}}$$

$$\text{THRUST} = W_L \mu \cos \theta + [(W_L / 386.4) (v/t_{\text{acc}})] + W_L \sin \theta + F_{\text{applied}}$$

Sample Calculations: Calculate the thrust required to accelerate a 200 pound mass to 8 inches per second in an acceleration time of 0.2 seconds. Calculate this thrust at inclination angles(θ) of 0°, 90° and 30°. Assume that there is a 25 pound spring force that is applied against the acceleration.

$$W_L = 200 \text{ lbm}, v = 8.0 \text{ in/sec.}, t_a = 0.2 \text{ sec.}, F_{\text{app.}} = 25 \text{ lbf}, \mu = 0.15$$

$$\theta = 0^\circ$$

$$\begin{aligned} \text{THRUST} &= W_L \mu \cos \theta + [(W_L / 386.4) (v/t_{\text{acc}})] + W_L \sin \theta + F_{\text{applied}} \\ &= (200)(0.15)(1) + [(200/386.4)(8.0/0.2)] + (200)(0) + 25 \\ &= 30 \text{ lbs} + 20.73 \text{ lbs} + 0 \text{ lbs} + 25 \text{ lbs} = \mathbf{75.73 \text{ lbs force}} \end{aligned}$$

$$\theta = 90^\circ$$

$$\begin{aligned} \text{THRUST} &= W_L \mu \cos \theta + [(W_L / 386.4) (v/t_{\text{acc}})] + W_L \sin \theta + F_{\text{applied}} \\ &= (200)(0.15)(0) + [(200/386.4)(8.0/0.2)] + (200)(1) + 25 \\ &= 0 \text{ lbs} + 20.73 \text{ lbs} + 200 \text{ lbs} + 25 \text{ lbs} = \mathbf{245.73 \text{ lbs force}} \end{aligned}$$

$$\theta = 30^\circ$$

$$\begin{aligned} \text{THRUST} &= W_L \mu \cos \theta + [(W_L / 386.4) (v/t_{\text{acc}})] + W_L \sin \theta + F_{\text{applied}} \\ &= (200)(0.15)(0.866) + [(200/386.4)(8.0/0.2)] + (200)(0.5) + 25 \\ &= 26 \text{ lbs} + 20.73 \text{ lbs} + 100 + 25 = \mathbf{171.73 \text{ lbs force}} \end{aligned}$$

Angle of Inclination

90°	Note: at $\theta = 0^\circ$ $\cos \theta = 1; \sin \theta = 0$ at $\theta = 90^\circ$ $\cos \theta = 0; \sin \theta = 1$
0°	
-90°	

It is necessary to calculate the required thrust for an application during each portion of the move profile, and determine the worst case criteria. The linear actuator should then be selected based on those values. The calculations at the right show calculations during acceleration which is often the most demanding segment of a profile.

Motor Torque Calculations

When selecting an actuator system it is necessary to determine the required motor torque to perform the given application. These calculations can then be compared to the torque ratings of the given amplifier and motor combination that will be used to control the actuator's velocity and position.

When the system uses a separate motor and screw, like the FT actuator, the ratings for that motor and amplifier are consulted. In the case of the GSX Series actuators with their integral brushless motors, the required torque divided by the torque constant of the motor (Kt) must be less than the current rating of the GSX or SLM motor.

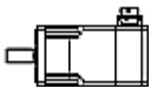
Inertia values and torque ratings can be found in the GSX, FT and SLM/SLG Series product specifications.

For the GSX Series the screw and motor inertia are combined.

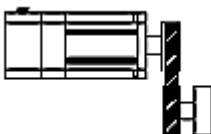
Motor with screw (GSX, GS, GSM & FT)



Motor & motor with reducer (SLM/SLG)



Motor with belt and pulley



Terms and (units)

λ	= Required motor torque, lbf-in (N-m)
λa	= Required motor acceleration torque, lbf-in (N-m)
F	= Applied force load, non inertial, lbf (N)
S	= Screw lead, in (m)
R	= Belt or reducer ratio
T_L	= Torque at driven load lbf-in (N-m)
v_L	= Linear velocity of load in/sec (m/sec)
ω_L	= Angular velocity of load rad/sec
ω_m	= Angular velocity of motor rad/sec
η	= Screw or ratio efficiency ($\cong 85\%$ for roller screws)
g	= Gravitational constant, 386.4 in/s ² (9.75 m/s ²)
α	= Angular acceleration of motor, rad/s ²
m	= Mass of the applied load, lb (N)
J_L	= Reflected Inertia due to load, lbf-in-s ² (N-m-s ²)
J_r	= Reflected Inertia due to ratio, lbf-in-s ² (N-m-s ²)
J_s	= Reflected Inertia due to external screw, lbf-in-s ² (N-m-s ²)
J_m	= Motor armature inertia, lbf-in-s ² (N-m-s ²)
L	= Length of screw, in (m)
ρ	= Density of screw material, lb/in ³ (kg/m ³)
r	= radius of screw, in (m)
π	= pi (3.14159)

Velocity Equations

Screw drive: $v_L = m \cdot S / 2\pi$ in/sec (m/sec)

Belt or gear drive: $\omega_m = \omega_L \cdot R$ rad/sec

Torque Equations

Torque Under Load

Screw drive (GSX, FT or separate screw): $\lambda = \frac{S \cdot F}{2 \cdot \pi \cdot \eta}$ lbf-in (N-m)

Belt and Pulley drive: $\lambda = T_L / R \cdot \eta$ lbf-in (N-m)

Gear or gear reducer drive: $\lambda = T_L / R \cdot \eta$ lbf-in (N-m)

Torque Under Acceleration

$\lambda a = (J_m + J_r + (J_s + J_L) / R^2) \alpha$ lbf-in

α = angular acceleration = ((RPM / 60) x 2 π) / t_{acc}, rad/sec².

$$J_s = \frac{\pi \cdot L \cdot \rho \cdot r^4}{2 \cdot g} \text{ lb-in-s}^2 \text{ (N-m-s}^2 \text{)}$$

Total Torque per move segment

$$\lambda T = \lambda a + \lambda \text{ lbf-in (N-m)}$$

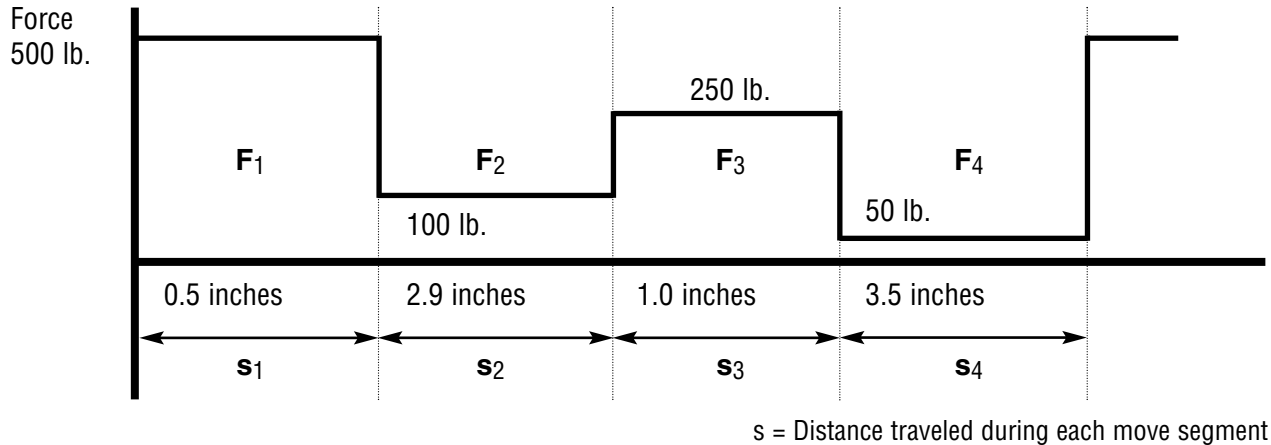
Calculating Estimated Travel Life of Exlar Linear Actuators

Mean Load Calculations

For accurate lifetime calculations of a roller screw in a linear application, the cubic mean load

should be used. Following is a graph showing the values for force and distance as well as the calculation for cubic mean load.

Forces are shown for example purposes. Negative forces are shown as positive for calculation.



Cubic Mean Load Equation

$$\sqrt[3]{\frac{F_1^3 s_1 + F_2^3 s_2 + F_3^3 s_3 + F_4^3 s_4}{s_1 + s_2 + s_3 + s_4}}$$

Value from example numbers is 225.8 lbs.

Lifetime Calculations

The expected L_{10} life of a roller screw is expressed as the linear travel distance that 90% of the screws are expected to meet or exceed before experiencing metal fatigue. The mathematical formula that defines this value is below. *The life is in millions of inches (mm).* This standard L_{10} life calculation is what is expected of 90% of roller screws manufactured and is not a guarantee. Travel life estimate is based on a properly maintained screw that is free of contaminants and properly lubricated. Higher than 90% requires de-rating according to the following factors:

95% x 0.62	96% x 0.53
97% x 0.44	98% x 0.33
99% x 0.21	

Single (non-preloaded) nut:

$$L_{10} = \left(\frac{C}{F}\right)^3 \times S$$

Preloaded (split) nut:

$$L_{10} = \left(L_{10(1)}^{-10/9} + L_{10(2)}^{-10/9}\right)^{-9/10}$$

where:

L_{10} = Travel life in millions of inches (mm)

$L_{10(1)}$ = Expected life in the extend direction, as determined by the single nut lifetime equation

$L_{10(2)}$ = Expected life in the retract direction, as determined by the single nut lifetime equation

Note: The dynamic load rating of zero backlash, preloaded screws is 63% of the dynamic load rating of the standard non-preloaded screws. The calculated travel life of a preloaded screw will be 25% of the calculated travel life of the same size and lead of a non-preloaded screw for the same application.

Total Thrust Calculations

Terms and (units)

- THRUST** = Total linear force-lbf (N)
F_{friction} = Force from friction-lbf (N)
F_{acc} = Acceleration force-lbf (N)
F_{gravity} = Force due to gravity-lbf (N)
F_{applied} = Applied forces-lbf (N)
 386.4 = Acceleration of gravity -in/sec²
 (9.8 m/sec²)

Variables

- θ** = Angle of inclination - deg = _____
t_{acc} = Acceleration time - sec = _____
v = Change in velocity - in/sec (m/s) . . = _____
μ = Coefficient of sliding friction = _____
W_L = Weight of Load-lbm (kg) = _____
F_{applied} = Applied forces-lbf (N) = _____

Thrust Calculation Equations

$$\text{THRUST} = [F_{\text{friction}}] + [F_{\text{acceleration}}] + F_{\text{gravity}} + F_{\text{applied}}$$

$$\text{THRUST} = [W_L \times \mu \times \cos\theta] + [(W_L / 386.4) \times (v / t_{\text{acc}})] + W_L \sin\theta + F_{\text{applied}}$$

$$\text{THRUST} = [() \times () \times ()] + [(/ 386.4) \times (/)] + [() ()] + ()$$

$$\text{THRUST} = [] + [() \times ()] + [] + ()$$

= _____ lbf.

Calculate the thrust for each segment of the move profile. Use those values in calculations below.
Use the units from the above definitions.

Cubic Mean Load Calculations

$$\sqrt[3]{ \frac{ F_1^3 s_1 + F_2^3 s_2 + F_3^3 s_3 + F_4^3 s_4 }{ s_1 + s_2 + s_3 + s_4 } }$$

- | | | |
|------------------------------|------------------------------|--|
| F₁ = _____ | S₁ = _____ | F₁³ t₁ = _____ |
| F₂ = _____ | S₂ = _____ | F₂³ t₂ = _____ |
| F₃ = _____ | S₃ = _____ | F₃³ t₃ = _____ |
| F₄ = _____ | S₄ = _____ | F₄³ t₄ = _____ |

Move Profiles may have more or less than four components. Adjust your calculations accordingly.

Torque Calculations

Terms and (units)

λ = Torque, lb-in (N-m)	=	_____
F = Applied Load, non inertial, lbf (N)	=	_____
S = Screw lead, in (m)	=	_____
η = Screw or ratio efficiency (~85% for roller screws)	=	_____
g = Gravitational constant, 386 in/s ² (9.8 m/s ²)	=	_____
α = Acceleration of motor, rad/s ²	=	_____
R = Belt or reducer ratio	=	_____
T_L = Torque at driven load, lbf-in (N-m)	=	_____
v_L = Linear velocity of load, in/sec (m/sec)	=	_____
ω_L = Angular velocity of load, rad/sec	=	_____
ω_m = Angular velocity of motor, rad/sec	=	_____
m = Mass of the applied load, lbm (kg)	=	_____
J_R = Reflected Inertia due to ratio, lb-in-s ² (N-m-s ²)	=	_____
J_S = Reflected Inertia due to screw, lb-in-s ² (N-m-s ²)	=	_____
J_L = Reflected Inertia due to load, lb-in-s ² (N-m-s ²)	=	_____
J_M = Motor armature inertia, lb-in-s ² (N-m-s ²)	=	_____
π = pi (3.14159)	=	3.14159
K_t = Motor Torque constant, lb-in/amp (N-m/amp)	=	_____

* For the GS Series **J_S** and **J_M** are one value from the GS Specifications.

Torque Equations

Torque From Calculated Thrust.

$$\lambda = \frac{SF}{2 \cdot \pi \cdot \eta} \text{ lb-in (N-m)} = (\quad) \times (\quad) / 2\pi(0.85) = (\quad) \times (\quad) / 5.34 = \underline{\hspace{2cm}}$$

Torque Due To Load, Rotary.

Belt and pulley drive: $\lambda = T_L / R \eta$ lbf-in (N-m)

Gear or gear reducer drive: $\lambda = T_L / R\eta$ lbf-in (N-m)

Torque During Acceleration due to screw, motor, load and reduction, linear or rotary.

$$\lambda = (J_m + (J_s + J_L) / R^2) \alpha \text{ lb-in (N-m)} = [(\quad) + (\quad + \quad) / (\quad)] (\quad) = \underline{\hspace{2cm}}$$

Total Torque = Torque from calculated Thrust + Torque due to motor, screw and load

$$(\quad) + (\quad) + (\quad) = \underline{\hspace{2cm}}$$

Motor Current = $\lambda / K_t = (\quad) / (\quad) = \underline{\hspace{2cm}}$

Exlar Application Worksheet

FAX to:
Exlar Corporation
(952) 368-4877
Attn: Applications Engineering

Date: _____

Company Name: _____

Address: _____

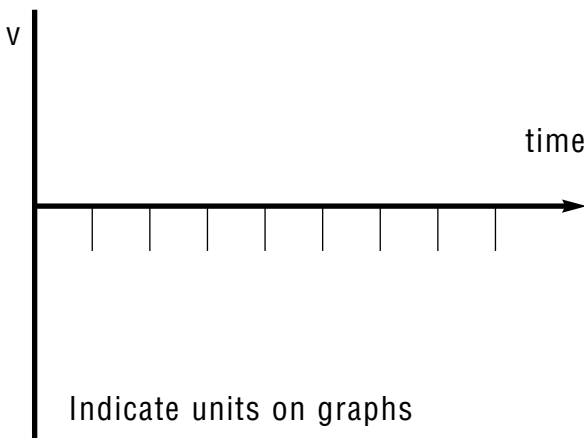
City: _____ State: _____ Zip Code: _____

Phone: _____ Fax: _____

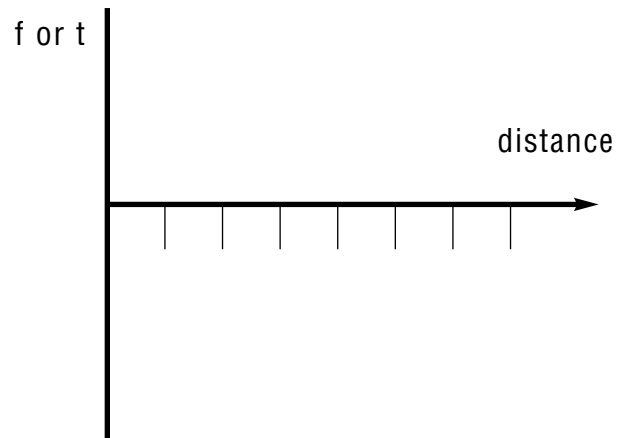
Contact: _____ Title: _____

Sketch / Describe Application

Velocity vs. Time



Force or Torque vs. Distance



Exlar Application Worksheet

Date: _____ Contact: _____ Company: _____

Stroke & Speed Requirements

Maximum Stroke Needed _____ inches (mm), revs
 Index Stroke Length _____ inches (mm), revs
 Index Time _____ sec
 Max Speed Requirements _____ in/sec (mm/sec), revs/sec
 Min Speed Requirements _____ in/sec (mm/sec), revs/sec
 Required Positional Accuracy _____ inches (mm), arc min

Load & Life Requirements

Gravitational Load _____ lb (N)
 External Applied Load _____ lbf (N)
 Inertial Load _____ lbf (N)
 Friction Load _____ lbf (N)
 Rotary Inertial Load _____ lbf-in-sec² (kg-m²)
 or rotary mass, radius of gyr. _____ lb (kg) _____ in (mm)
 Side Load (rot. or lin. actuator) _____ lb (N)
 Force Direction ___ Extend ___ Retract ___ Both
 Actuator Orientation ___ Vertical Up ___ Vertical Down ___ Horizontal
 ___ Fixed Angle ___ Degrees from Horizontal
 ___ Changing Angle ___ to _____

Cycling Rate _____ Cycles/min/hr/day
 Operating Hours per Day _____ Hours
 Life Requirement _____ Cycles/hr/inches/mm

Configuration

Mounting: ___ Side ___ Flange ___ Ext Tie Rod ___ Clevis ___ Trunnion
 Rod End: ___ Male ___ Female ___ Sph Rod Eye ___ Rod Eye ___ Clevis
 Rod Rotation Limiting ___ Appl Inherent ___ External Req'd
 Holding Brake Req'd: ___ Yes ___ No
 Cable Length _____ ft (m)

Reference Tables

ROTARY INERTIA

To obtain a conversion from A to B, multiply by the value in the table.

A	B	kg-m ²	kg-cm ²	g-cm ²	kgf-m-s ²	kgf-cm-s ²	gf-cm-s ²	oz-in ²	ozf-in-s ²	lb-in ²	lbf-in-s ²	lb-ft ²	lbf-ft-s ²
kg-m ²	1	10 ⁴	10 ⁷	10 ¹	0.10192	1.01972x10 ⁴	1.01972x10 ⁴	5.46745x10 ⁴	1.41612x10 ²	3.41716x10 ³	8.850732	23.73025	0.73756
kg-cm ²	10 ⁻⁴	1	10 ³	10 ³	1.01972x10 ⁵	1.01972x10 ³	1.01972	5.46745	1.41612x10 ²	0.341716	8.85073x10 ⁻⁴	2.37303x10 ⁻³	7.37561x10 ⁻⁵
g-cm ²	10 ⁻⁷	10 ⁻³	1	1	1.01972x10 ⁻⁸	1.01972x10 ⁻⁶	1.01972x10 ⁻³	5.46745x10 ⁻³	1.41612x10 ⁻⁵	3.41716x10 ⁻⁴	8.85073x10 ⁻⁷	2.37303x10 ⁻⁶	7.37561x10 ⁻⁸
kgf-m-s ²	9.80665	9.80665x10 ⁴	9.80665x10 ⁷	1	10 ²	10 ⁵	10 ⁵	5.36174x10 ⁵	1.388674x10 ³	3.35109x10 ⁴	86.79606	2.32714x10 ²	7.23300x10 ⁻²
kgf-cm-s ²	9.80665x10 ⁻²	9.80665x10 ²	9.80665x10 ⁵	10 ⁻²	10 ⁻²	10 ⁵	10 ⁵	5.36174 x10 ³	13.8874	3.35109x10 ⁻²	0.86796	2.32714	7.23300x10 ⁻²
gf-cm-s ²	9.80665x10 ⁻⁵	0.980665	9.80665x10 ²	9.80665x10 ²	10 ⁻⁵	1	1	5.36174	1.38874 x10 ⁻²	0.335109	8.67961x10 ⁻⁴	2.32714x10 ⁻³	7.23300x10 ⁻⁵
oz-in ²	1.82901x10 ⁻⁵	0.182901	1.82901x10 ²	1.86505x10 ²	1.86505x10 ⁻⁶	0.186506	1	2.59008 x10 ⁻³	2.59008 x10 ⁻³	6.25 x10 ⁻²	1.61880x10 ⁻⁴	4.34028x10 ⁻⁴	1.34900x10 ⁻³
lb-in ²	7.06154x10 ⁻³	70.6154	7.06154x10 ⁴	7.20077x10 ⁴	7.20077x10 ²	72.0077	3.86089x10 ²	1	1	24.13045	6.25 x10 ⁻²	0.167573	5.20833x10 ⁻⁴
lb-in ²	2.92641x10 ⁻⁴	2.92641	2.92641x10 ³	2.98411x10 ⁵	2.98411x10 ³	2.98411	16	4.1414 x10 ²	4.1414 x10 ²	1	2.59008x10 ⁻³	6.94444x10 ⁻³	2.15840x10 ⁻⁴
lbf-in-s ²	0.112985	1.12985x10 ³	1.12985x10 ⁶	1.15213x10 ²	1.15213 x10 ³	1.15213	6.1774 x10 ³	16	16	3.86088x10 ²	1	2681175	8.3333x10 ⁻²
lbf-ft ²	4.21403x10 ⁻²	4.21403x10 ²	4.21403x10 ⁵	4.29711x10 ³	4.29711 x10 ³	4.29711	2.304 x10 ³	2.304 x10 ³	5.96755	144	0.372971	1	3.10809x10 ⁻²
lbf-ft-s ²	1.35583	1.35582x10 ⁴	1.35582x10 ⁷	0.138255	13.82551	1.38255x10 ⁴	7.41289x10 ⁴	192	192	4.63306x10 ³	12	32.17400	1

TORQUE

To obtain a conversion from A to B, multiply A by the value in the table.

A	B	N-m	N-cm	dyn-cm	kg-m	kg-cm	g-cm	oz-in	ft-lb	in-lb
N-m	1	10 ²	10 ⁷	10 ⁷	0.109716	10.19716	1.019716 x10 ⁴	141.6199	0.737562	8.85074
N-cm	10 ²	1	10 ⁵	10 ⁵	1.019716 x10 ³	0.1019716	1.019716 x10 ²	1.41612	7.37562 x10 ⁻³	8.85074 x10 ⁻²
dyn-cm	10 ⁻⁷	10 ⁻⁵	1	1	1.019716 x10 ⁻⁸	1.019716 x10 ⁻⁶	1.019716 x10 ⁻³	1.41612 x10 ⁻⁵	7.2562 x10 ⁻⁸	8.85074 x10 ⁻⁷
kg-m	9.80665	980665x10 ²	9.80665 x10 ⁷	9.80665 x10 ⁷	1	10 ²	10 ⁵	1.38874 x10 ³	7.23301	86.79624
kg-cm	9.80665x10 ⁻²	9.80665	9.80665 x10 ⁵	9.80665 x10 ⁵	10 ⁻²	1	10 ³	13.8874	7.23301 x10 ⁻²	0.86792
g-cm	9.80665x10 ⁻⁵	9.80665x10 ⁻³	9.80665 x10 ²	9.80665 x10 ²	10 ⁻⁵	10 ⁻³	1	1.38874 x10 ⁻²	7.23301 x10 ⁻⁵	8.679624 x10 ⁻⁴
oz-in	7.06155x10 ⁻³	0.706155	7.06155 x10 ⁴	7.06155 x10 ⁴	7.20077 x10 ⁻⁴	7.20077 x10 ⁻²	72.077	1	5.20833 x10 ⁻³	6.250 x10 ⁻²
ft-lb	1.35582	1.35582x10 ²	1.35582 x10 ⁷	1.35582 x10 ⁷	0.1382548	13.82548	1.382548 x10 ⁴	192	1	12
in-lb	0.113	11.2985	1.12985 x10 ⁶	1.12985 x10 ⁶	1.15212 x10 ⁻²	1.15212	1.15212 x10 ³	16	8.33333 x10 ⁻²	1

COMMON MATERIAL DENSITIES

Material	oz/in ³	gm/cm ³
Aluminum (cast or hard drawn)	1.54	2.66
Brass (cast or rolled)	4.80	8.30
Bronze (cast)	4.72	8.17
Copper (cast or hard drawn)	5.15	8.91
Plastic	0.64	1.11
Steel (hot or cold rolled)	4.48	7.75
Wood (hard)	0.46	0.80
Wood (soft)	0.28	0.58

COEFFICIENTS OF SLIDING FRICTION

Materials in contact	μ
Steel on Steel (dry)	0.58
Steel on Steel (lubricated)	0.15
Aluminum on Steel	0.45
Copper on Steel	0.36
Brass on Steel	0.44
Plastic on Steel	0.20
Linear Bearings	0.001