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 maximum 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.

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 send to Exlar for sizing. Reference tables for common unit conversions and motion system constants are included at the end of the section.
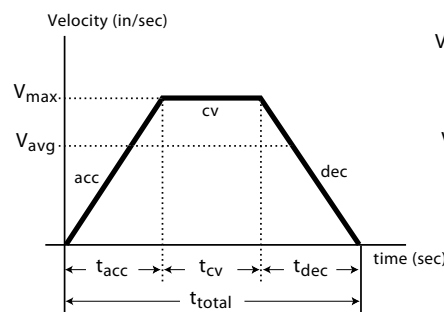
Linear Move Profile Calculations

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/sec^2 (m/sec^2)
dec = decel-in/sec^2 (m/sec^2)
cv = constant vel.-in/sec (m/sec)
D = total move distance-in (m)
or revolutions (rotary)

Standard Equations

V_{avg} = D / t_{total}
If t_{acc} = t_{dec} **Then:** V_{max} =
$(t_{total}/(t_{total}-t_{acc})(V_{avg})$
and
D = Area under profile curve
D = $(1/2(t_{acc}+t_{dec})+t_{cv})(V_{max})$

Trapezoidal Move Profile

Triangular Move Profile

Trapezoidal Equations

If t_{acc} = t_{cv} = t_{dec} **Then:**
V_{max} = 1.5 (V_{avg})
D = $(2/3)$ (t_{total}) (V_{max})
acc = dec = $\dfrac{V_{max}}{t_{acc}}$
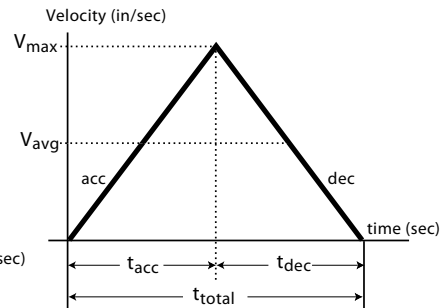
Triangular Equations

If t_{acc} = $t_{total}/2$ **Then:**
V_{max} = 2.0 (V_{avg})
D = $(1/2)$ (t_{total}) (V_{max})
acc = dec = $\dfrac{V_{max}}{t_{acc}}$

Terms and (units)

THRUST	= Total linear force-lbf (N)
Ø	= Angle of inclination (deg)
Ffriction	= Force from friction-lbf (N)
tacc	= Acceleration time (sec)
Facc	= Acceleration force-lbf (N)
v	= Change in velocity-in/sec (m/s)
Fgravity	= Force due to gravity-lbf (N)
μ	= Coefficient of sliding friction
Fapplied	= Applied forces-lbf (N)
	(refer to table on page 136 for different materials)
WL	= Weight of Load-lbf (N)
g	= 386.4: Acceleration of gravity - in/sec^2 (9.8 m/sec^2)

Thrust Calculation Equations

THRUST = **F**friction + [**F**acceleration] + **F**gravity + **F**applied

THRUST = **W**Lμcosø + [(**W**L /386.4) (**v**/tacc)] + **W**Lsinø + **F**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(ø) of 0˚, 90˚ and 30˚. Assume that there is a 25 pound spring force that is applied against the acceleration.

WL = 200 lbm, v = 8.0 in/sec., **t**a = 0.2 sec., **F**app. = 25 lbf, μ = 0.15

ø = 0˚

THRUST = **W**Lμcosø + [(**W**L /386.4) (**v**/tacc)] + **W**Lsinø + **F**applied
= (200)(0.15)(1) + [(200/386.4)(8.0/0.2)] + (200)(0) + 25

= 30 lbs + 20.73 lbs + 0 lbs + 25 lbs = **75.73 lbs force**

ø = 90˚

THRUST = **W**Lμcosø + [(**W**L /386.4) (**v**/tacc)] + **W**Lsinø + **F**applied
= (200)(0.15)(0) + [(200/386.4)(8.0/0.2)] + (200)(1) + 25

= 0 lbs + 20.73 lbs + 200 lbs + 25 lbs = **245.73 lbs force**

ø = 30˚

THRUST = **W**Lμcosø + [(**W**L /386.4) (**v**/tacc)] + **W**Lsinø + **F**applied
= (200)(0.15)(0.866) + [(200/386.4)(8.0/0.2)] + (200)(0.5) + 25

= 26 lbs + 20.73 lbs + 100 + 25 = **171.73 lbs force**

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.

Angle of Inclination

Note: at ø = 0˚
cosø = 1; sinø = 0
at ø = 90˚
cosø = 0; sinø = 1

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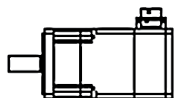
Inertia values and torque ratings can be found in the GSX, FT, and SLM/SLG Series product specifications.

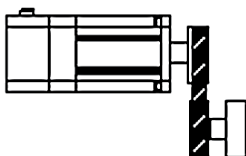For the GSX Series the screw and motor inertia are combined.

Motor with screw (GSX, FT, & EL)

Motor & motor with reducer (SLM/SLG & ER)

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 (kN)

ℓ = Screw lead, in (mm)

R = Belt or reducer ratio

TL = Torque at driven load lbf-in (N-m)

vL = Linear velocity of load in/sec (m/sec)

ωL = Angular velocity of load rad/sec

ωm = Angular velocity of motor rad/sec

η = Screw or ratio efficiency

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)

JL = Reflected Inertia due to load, lbf-in-s^2 (N-m-s^2)

Jr = Reflected Inertia due to ratio, lbf-in-s^2 (N-m-s^2)

Js = Reflected Inertia due to external screw, lbf-in-s^2 (N-m-s^2)

Jm = 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)

C$_a$ = Dynamic load rating, lbf (N)

Velocity Equations

Screw drive: $\mathbf{V}_L = \omega m \cdot S / 2\pi$ in/sec (m/sec)

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

Torque Equations

Torque Under Load

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

Belt and Pulley drive: $\lambda = \mathbf{T}_L / R\,\eta$ lbf-in (N-**m**)

Gear or gear reducer drive: $\lambda = \mathbf{T}_L / R\,\eta$ lbf - in (N-**m**)

Torque Under Acceleration

$\lambda a = (\mathbf{J}_m + \mathbf{J}_R + (\mathbf{J}_s + \mathbf{J}_L)/R^2)\alpha$ lbf-in

α = angular acceleration = $((RPM / 60) \times 2\pi) / \mathbf{t}_{acc}$, rad/sec^2.

$\mathbf{J}_S = \dfrac{\pi \cdot \mathbf{L} \cdot \rho \times r^4}{2 \cdot g}$ lb - in - s^2 (N - **m** - s^2)

Total Torque per move segment

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

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.

Force
500 lbs

250 lbs

| F_1 | F_2 | F_3 | F_4 |

100 lbs

50 lbs

| 0.5 inches | 2.9 inches | 1.0 inches | 3.5 inches |
| S_1 | S_2 | S_3 | S_4 |

S = Distance traveled during each move segment
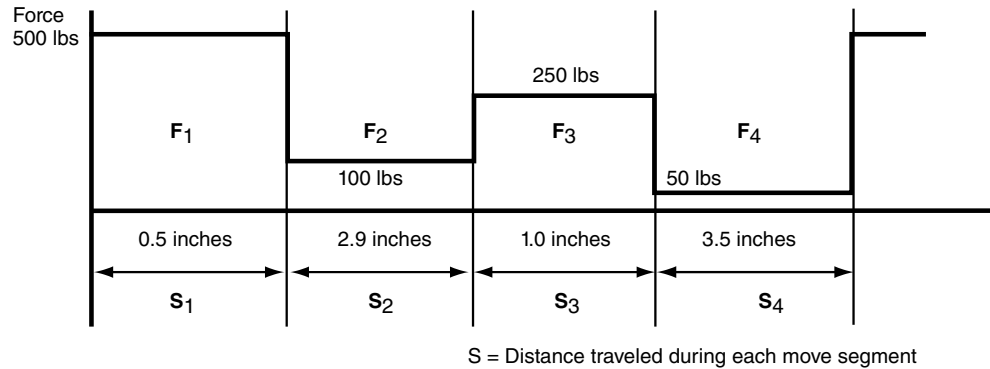
Cubic Mean Load Equation

$$F_{cml} = \sqrt[3]{\frac{F_1^3 S_1 + F_2^3 S_2 + F_3^3 S_3 + F_4^3 S_4}{S_1 + S_2 + S_3 + S_4}}$$

Value from example numbers is 217 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:

$$L_{10} = \left(\frac{C_a}{F_{cml}}\right)^3 \times \ell$$

Short Stroke Lifetime Calculations

If your application requires high force over a stroke length shorter than the length of the rollers/nut, please contact Exlar for derated life calculations. You may also download the article "Calculating Life Expectancy" at www.exlar.com.

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)		Variables		
THRUST = Total linear force-lbf (N)		Ø	= Angle of inclination - deg........................ = _____
$\mathbf{F}_{friction}$ = Force from friction-lbf (N)		**t**acc	= Acceleration time - sec........................... = _____
$\mathbf{F}_{acc}$ = Acceleration force-lbf (N)		**v**	= Change in velocity - in/sec (m/s)........... = _____
$\mathbf{F}_{gravity}$ = Force due to gravity-lbf (N)		μ	= Coefficient of sliding friction .... = _____
$\mathbf{F}_{applied}$ = Applied forces-lbf (N)		$\mathbf{W}_L$	= Weight of Load-lbm (kg)........................ = _____
386.4 = Acceleration of gravity - in/sec^2 (9.8 m/sec^2)		$\mathbf{F}_{applied}$	= Applied forces-lbf (N) .... = _____

Thrust Calculation Equations

THRUST = [$\mathbf{F}_{friction}$] + [$\mathbf{F}_{acceleration}$] + $\mathbf{F}_{gravity}$ + $\mathbf{F}_{applied}$

THRUST = [$\mathbf{W}_L$ x μ x cosø] + [($\mathbf{W}_L$ /386.4) x (**v / t**$_{acc}$)] + $\mathbf{W}_L$sinø + $\mathbf{F}_{applied}$

THRUST = [( )x( )x( )] + [(/386.4) x (/)] + [( ) ( )] + ( )

THRUST = [ ] + [( ) x ( )] + [ ] + ( )

= _____ 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

$$\sqrt[3]{\frac{F_1^3\,S_1 + F_2^3\,S^2 + F_3^3\,S_3 + F_4^3\,S_4}{S_1 + S_2 + S_3 + S_4}}$$

F_1= _____ S_1= _____ $F_1^3\,S_1$ = _____

F_2= _____ S_2= _____ $F_2^3\,S_2$ = _____

F_3= _____ S_3= _____ $F_3^3\,S_3$ = _____

F_4= _____ S_4= _____ $F_4^3\,S_4$ = _____

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/s2 (9.8 m/s2).. = --------------------

α = Acceleration of motor, rad/s2... = --------------------

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-s2 (N-m-s2) .... = --------------------

J_S = Reflected Inertia due to screw, lb-in-s2 (N-m-s2) .... = --------------------

J_L = Reflected Inertia due to load, lb-in-s2(N-m-s2).. = --------------------

J_M = Motor armature inertia, lb-in-s2 (N-m-s2) .... = --------------------

π = pi .... = 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.

$\lambda = \dfrac{SF}{2 \cdot \pi \cdot \eta}$ lb - in (N - m) = (   ) x (   )/2π (0.85) = (   ) x (   )/5.34 = ----------------------------

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.

$l = (J_m + (J_S + J_L) / R^2) \alpha$ lb-in (N-**m**) = [(   ) + (+   ) / (   )] (   ) = ----------------------

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

(   ) + (   ) + (   ) = _____

Motor Current = λ / K_t = (   ) / (   ) = _____

Exlar Application Worksheet

Send to:

Exlar Automation

Email: cha_applications@curtisswright.com

Fax: (952) 368-4877

Attn: Applications Engineering

Date: _____ Company Name: _____

Address: _____

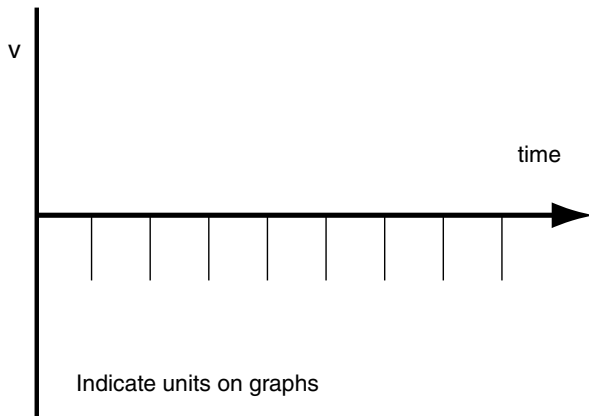City: _____ State: _____ Zip Code: _____

Phone: _____ Fax: _____

Contact: _____ Title: _____

Sketch/Describe Application

Velocity vs. Time

v

time

Indicate units on graphs

Force or Torque vs. Distance

f or t

distance
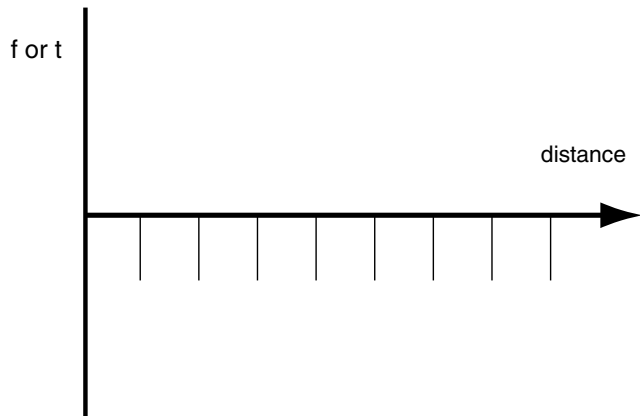
Exlar Application Worksheet

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-sec^2 (Kg-m^2)

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 Required

Holding Brake Required: _____ 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.

B \ A	Kg-m²	Kg-cm²	g-cm²	kgf-m-s²	kgf-cm-s²	gf-cm-s²	oz-in²	ozf-in-s²	lb-in²	lbf-in-s²	lb-ft²	lbf-ft-s²
Kg-m²	1	10^4	10^7	0.10192	10.1972	1.01972×10^4	5.46745×10^4	1.41612×10^2	3.41716×10^3	8.850732	23.73025	0.73756
Kg-cm²	10^{-4}	1	10^3	1.01972×10^5	1.01972×10^3	1.01972	5.46745	1.41612×10^{-2}	0.341716	8.85073×10^{-4}	2.37303×10^{-3}	7.37561×10^{-5}
g-cm²	10^{-7}	10^{-3}	1	1.01972×10^{-8}	1.01972×10^{-6}	1.01972×10^{-3}	5.46745×10^{-3}	1.41612×10^{-5}	3.41716×10^{-4}	8.85073×10^{-7}	2.37303×10^{-6}	7.37561×10^{-8}
kgf-m-s²	9.80665	9.80665×10^4	9.80665×10^7	1	10^2	10^5	5.36174×10^5	1.388674×10^3	3.35109×10^4	86.79606	2.32714×10^2	7.23300
kgf-cm-s²	9.80665×10^{-2}	9.80665×10^2	9.80665×10^5	10^{-2}	1	10^5	5.36174×10^3	13.8874	3.35109×10^2	0.86796	2.32714	7.23300×10^{-2}
gf-cm-s²	$9.80665 \times 10{-5}$	0.980665	9.80665×10^2	10^{-5}	10^{-3}	1	5.36174	1.38874×10^{-2}	0.335109	8.67961×10^{-4}	2.32714×10^{-3}	7.23300×10^{-5}
oz-in²	1.82901×10^{-5}	0.182901	1.82901×10^2	1.86505×10^{-6}	1.86505×10^{-4}	0.186506	1	2.59008×10^{-3}	6.25×10^{-2}	1.61880×10^{-4}	4.34028×10^{-4}	1.34900×10^{-3}
oz-in-s²	7.06154×10^{-3}	70.6154	7.06154×10^4	7.20077×10^4	7.20077×10^{-2}	72.0077	3.86089×10^2	1	24.13045	6.25×10^{-2}	0.167573	5.20833×10^{-4}
lb-in²	2.92641×10^{-4}	2.92641	2.92641×10^3	2.98411×10^5	2.98411×10^3	2.98411	16	4.14414×10^2	1	2.59008×10^{-3}	6.94444×10^{-3}	2.15840×10^{-4}
lbf-in-s²	0.112985	1.129×10^3	1.12985×10^6	1.15213×10^2	1.15213	1.51213×10^3	6.1774×10^3	16	3.86088×10^2	1	2681175	8.3333×10^{-2}
lbf-ft²	4.21403×10^{-2}	4.21403×10^2	4.21403×10^5	4.29711×10^3	0.429711	4.297114	2.304×10^3	5.96755	144	0.372971	1	3.10809×10^{-2}
lbf-ft-s²	1.35583	1.35582×10^4	1.35582×10^7	0.138255	13.82551	1.38255×10^4	7.41289×10^4	192	4.63306×10^3	12	32.17400	1

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

B \ A	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	0.109716	10.19716	1.019716×10^4	141.6199	0.737562	8.85074
N-cm	102	1	10^5	1.019716×10^3	0.1019716	1.019716×10^2	1.41612	7.37562×10^{-3}	8.85074×10^{-2}
dyn-cm	10-7	10^{-5}	1	1.019716×10^{-8}	1.019716×10^{-6}	1.019716×10^{-3}	1.41612×10^{-5}	7.2562×10^{-8}	8.85074×10^{-7}
Kg-m	9.80665	980665×10^2	9.80665×10^7	1	10^2	10^5	1.38874×10^3	7.23301	86.79624
Kg-cm	9.80665x10-2	9.80665	9.80665×10^5	10^{-2}	1	10^3	13.8874	7.23301×10^{-2}	0.86792
g-cm	9.80665x10-5	9.80665×10^{-3}	9.80665×10^2	10^{-5}	10^{-3}	1	1.38874×10^{-2}	7.23301×10^{-5}	8.679624×10^{-4}
oz-in	7.06155x10-3	0.706155	7.06155×10^4	7.20077×10^{-4}	7.20077×10^{-2}	72,077	1	5.20833×10^{-3}	6.250×10^{-2}
ft-lb	1.35582	1.35582×10^2	1.35582×10^7	0.1382548	13.82548	1.382548×10^4	192	1	12
in-lb	0.113	11.2985	1.12985×10^6	1.15212×10^{-2}	1.15212	1.15212×10^3	16	8.33333×10^{-2}	1

Common Material Densities

Material	oz/in³	gm/cm³
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

Standard Ratings for Exlar Actuators

The standard IP rating for Exlar Actuators is IP54S or IP65S. Ingress protection is divided into two categories: solids and liquids.

For example, in IP65S the three digits following "IP" represent different forms of environmental influence:
- The first digit represents protection against ingress of solid objects.
- The second digit represents protection against ingress of liquids.
- The suffix digit represents the state of motion during operation.

Digit 1 - Ingress of Solid Objects

The IP rating system provides for 6 levels of protection against solids.

1	Protected against solid objects over 50 mm e.g. hands, large tools.
2	Protected against solid objects over 12.5 mm e.g. hands, large tools.
3	Protected against solid objects over 2.5 mm e.g. large gauge wire, small tools.
4	Protected against solid objects over 1.0 mm e.g. small gauge wire.
5	Limited protection against dust ingress.
6	Totally protected against dust ingress.

Digit 2 - Ingress of Liquids

The IP rating system provides for 9 levels of protection against liquids.

1	Protected against vertically falling drops of water or condensation.
2	Protected against falling drops of water, if the case is positioned up to 15 degrees from vertical.
3	Protected against sprays of water from any direction, even if the case is positioned up to 60 degrees from vertical.
4	Protected against splash water from any direction.
5	Protected against low pressure water jets from any direction. Limited ingress permitted.
6	Protected against high pressure water jets from any direction. Limited ingress permitted.
7	Protected against short periods (30 minutes or less) of immersion in water of 1m or less.
8	Protected against long durations of immersion in water.
9	Protected against high-pressure, high-temperature wash-downs.

Suffix

S	Device standing still during operation	M	Device moving during operation

Notes