The HMK guide to Sizing of Servo Motors and Amplifier

Edition 2 - 08/02

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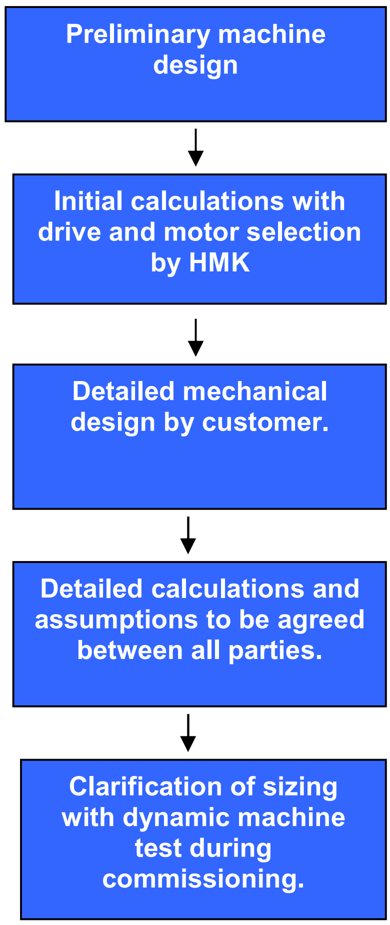
1. Introduction

This training manual is designed as an aid to machine designers and electrical engineers involved with the design, selection and operation of machines that incorporate Servodrives for position and speed control.

It is important that all parties involved in machine design and automation understand these calculations and use the information as a design aid.

The following process should be observed



2. Torque

It is important to examine the following data before deciding which servomotor and amplifier to select for an application. The reason for selecting a servodrive solution is normally because a fast acceleration or an accurate speed holding is required.

The following information is used to determine the torque required for a servomotor.

- **Load Torque** – This could be the torque require to move a mass or a torque that needs to be applied to perform an operation e.g. cutting, pressing etc
- **Friction Torque** – The force required to overcome friction.
- **Acceleration Torque** – The torque required to accelerate an inertia in a defined time.

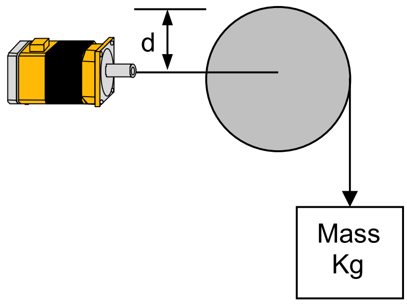
Torque is measured in Newton meters (Nm). 1Nm is the torque produced by a force of 1 Newton (N) acting on a radius of 1m.

Force is measured in Newtons (N). 1N = Mass in Kg x Gravity (9.81 ms^2)

2.1 – Load Torque

2.1.1 – Pulley, Pinion or Sprocket

T = F x d (Nm)

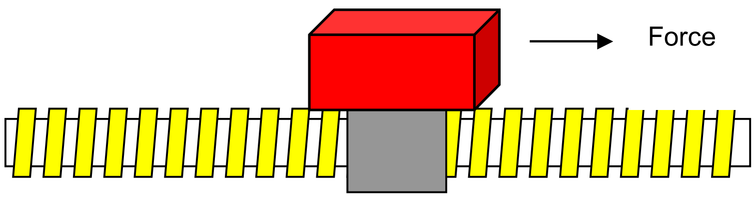


F = M x g (N)

Force (F) Newtons (N)
Distance (d) meters (m)

Please note – Distance (d) is the radius of the drive mechanism.

2.1.2 - Screw



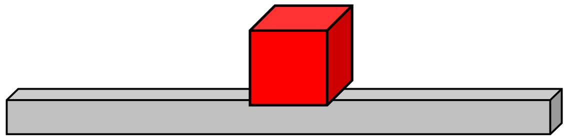
$$T = \frac{M \times g \times p}{2 \times \Pi \times \eta} \ (Nm)$$

M = Mass (Kg)
g = Acceleration due to gravity (ms^2)
Pitch (p) meters (m)
Efficiency (η) – Ball screw 0.8 to 0.9, Acme 0.2 to 0.35

2.2 Frictional Torque

This is the torque required to overcome friction. Typically loads will be supported on bearings and in many cases this will be a small value.

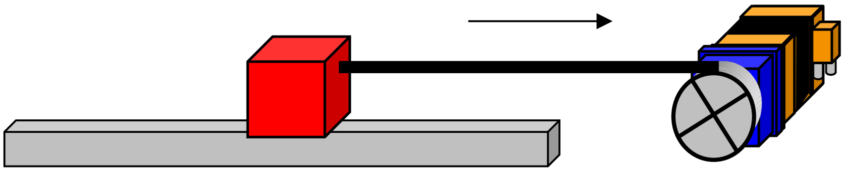
2.2.1 Mass on a linear bearing



$F = M \times g \times \mu$ (N)

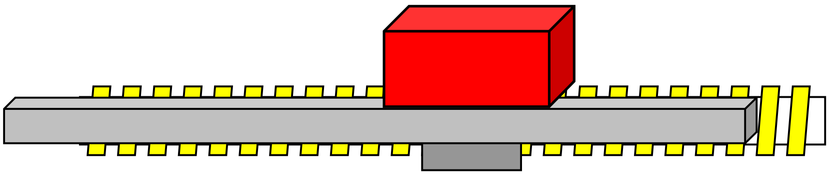
M = Mass of object
g = Acceleration due to gravity (ms^2)
μ = Coefficient of friction (Typically 0.1 for ball slides)

The torque required to overcome this force depends on the drive mechanism selected.



$T = F \times d$ (Nm)

2.2.2 Mass on a bearing driven by a screw

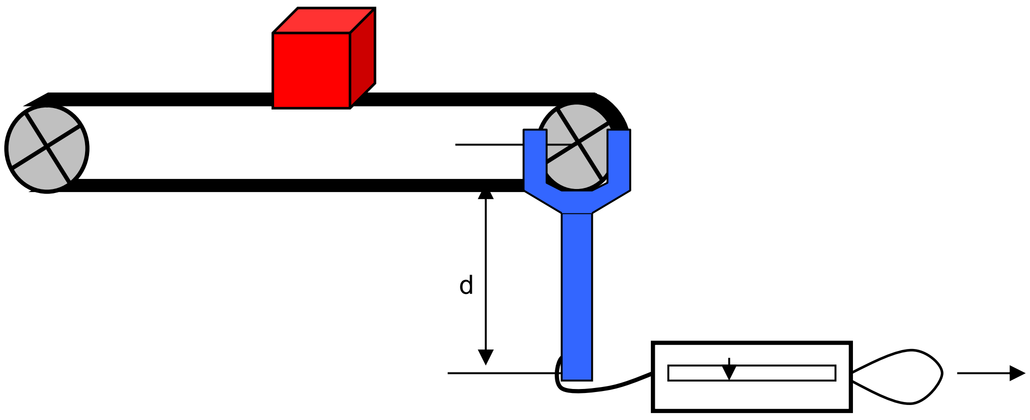


$$T = \frac{M \times g \times p \times \mu}{2 \times \Pi \times \eta} \text{ (Nm)}$$

M = Mass (Kg)
g = Acceleration due to gravity (ms^2)
Pitch (p) meters (m)
Efficiency (η) – Ball screw 0.8 to 0.9, Acme 0.2 to 0.35
μ = Coefficient of friction (Typically 0.1 for ball slides)

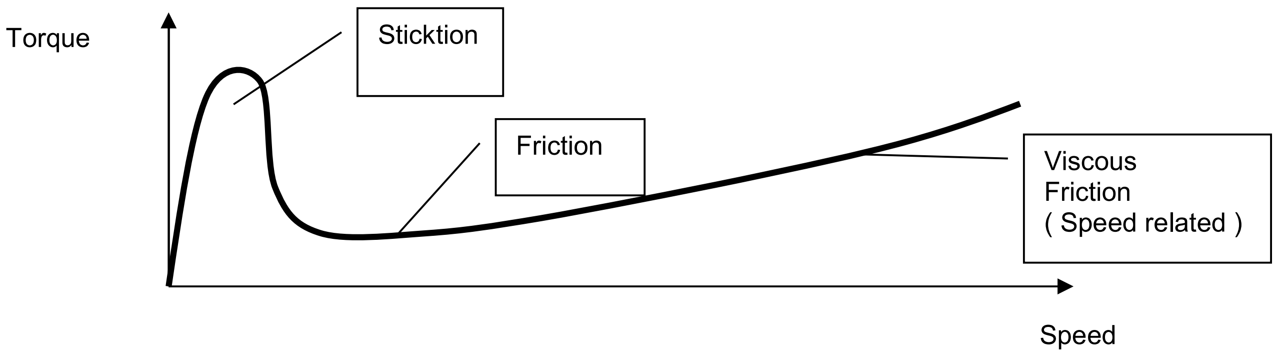
2.2.3 Spring Balance Test

It is also possible to mechanically test frictional torque using the “ Spring Balance Test “.



Use a spring balance to pull a mechanism at a radius and record the mass. (Kg)

You will discover that you will see an initial high mass to start movement (Sticktion), followed by a lower mass to maintain this motion (Friction), then in many applications a load might increase with velocity due to lubricant pressures etc (Viscous Friction).



To calculate the torque taken to overcome Sticktion :-

T = F x d (Nm)

F = M x g (N)

Selection Tip

Belt conveyors and guided chain traverses have high frictional losses when loaded. We would always advise the Spring Balance Test in these situations or assume 0.4 for coefficient of friction.

2.3 Acceleration / Braking Torque

Acceleration torque is the torque required to accelerate an inertia to a velocity.

Usually the torque to accelerate the inertial (J) is the most critical component of a servodrive solution.

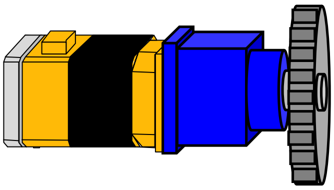
Acceleration torque is calculated by multiplying the inertia of a component (J) by the rate of acceleration (α) .

$T = J \times \alpha$ (Nm)

Selection Tip

As the inertia of the motor and gearbox also needs to be included in any calculations, you will need to initially select what you consider to be a suitable combination for the initial calculations and perhaps re-select later if it appears to be in appropriate.

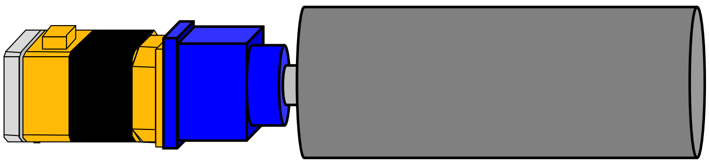
2.3.1 Inertia of a mass at a radius



$J = M \times r^2$ (Kgm^2)

Mass (M) Kg
Radius (r) m

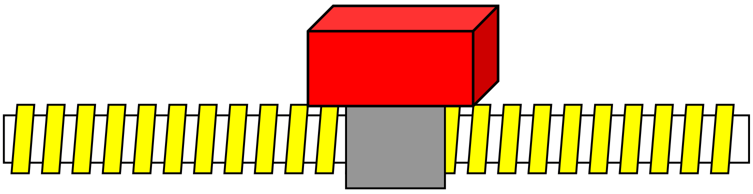
2.3.2 Inertia of a cylinder



$$J = \frac{\Pi}{32} \times \rho \times L \times d^4 \quad (Kgm^2)$$

L = Length (m)
d = diameter (m)
ρ = specific mass of material (Density)
Steel = 7850 Kgm^3
Stainless steel = 7930 Kgm^3
Aluminium = 2750 Kgm^3

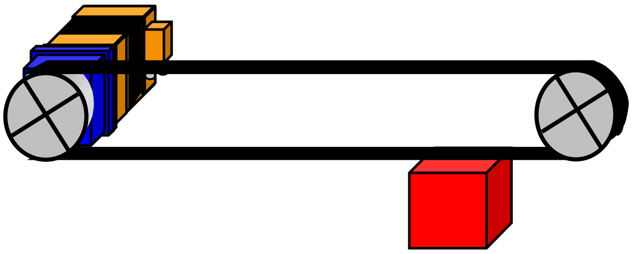
2.3.3 Inertia of a mass on a screw



$$J = W\left\{ \frac{P}{2\Pi} \right\}^2 \ (Kgm^2)$$

W = Mass (Kg)
P = Pitch (m)

2.3.4 Gear ratio and inertia



Once load inertia is calculated it must be divided by the gear ratio, squared to arrive at the reflected inertia seen at the motor shaft.

e.g. If load inertia is 0.01 Kgm^2 and gear ratio = 10:1 , reflected inertia = $\frac{0.01}{10^2}$ = 0.0001 Kgm^2

Selection Tip

To convert $Kgcm^3$ to Kgm^2 – Divide by 10,000

The referred load inertia should not be more than 10 times the motor inertia for high performance control.

2.3.5 Total inertia

Add the selected motor inertia and any gearbox inertia to the reflected inertia figure before calculating the torque required to accelerate an inertia.

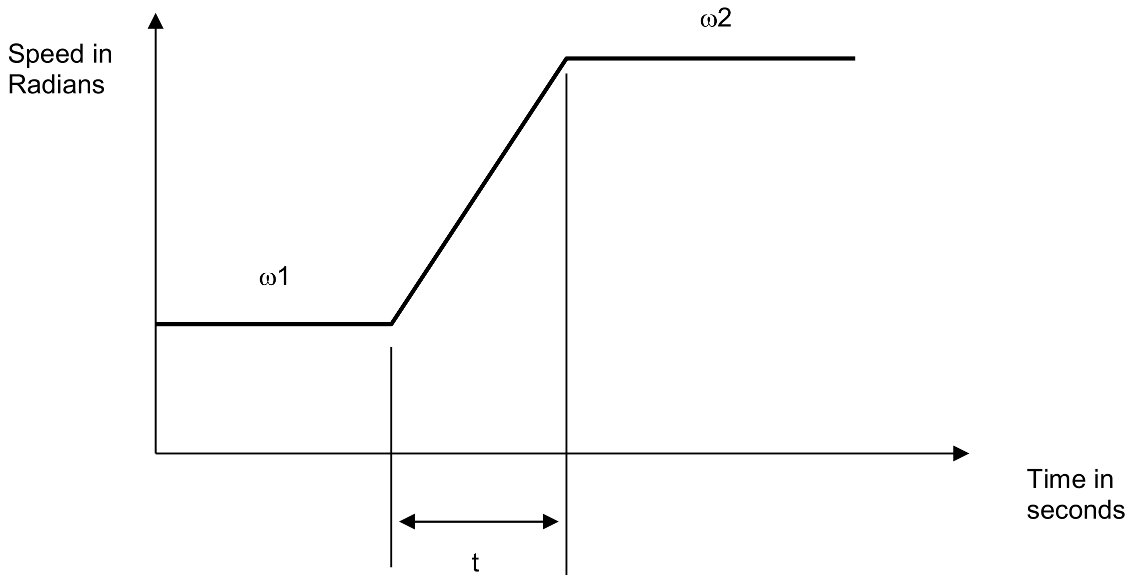
$$J_{total} = J_{load} + J_{motor} + J_{gearbox}$$

Selection Tip

All inertia should be calculated and then added together. If you decide to size based only on the largest mass, ensure you have sufficient overhead in your selection.

2.3.6 Rate of Acceleration

Rather than referring to the rate of acceleration in meters / second as in a motion control device, we define acceleration in terms rate of change of angular speed over a defined time



Angular speed (ω) = $\frac{2\Pi}{60}$ x n (Radians)

n = speed in rpm

Angular speed change = $\omega 1 - \omega 2$

Acceleration $\alpha = \frac{\omega}{t}$ (Radians/second ^{2})

t = acceleration time (seconds)

Selection Tip

As a guide we classify the acceleration rates as follows

1000 to 2000– Low performance
2000 to 5000 – Medium performance
5000 to 10,000 – High performance

3. Selecting a motor and amplifier

Once you have completed the initial round of calculations a motor and amplifier combination can be selected.

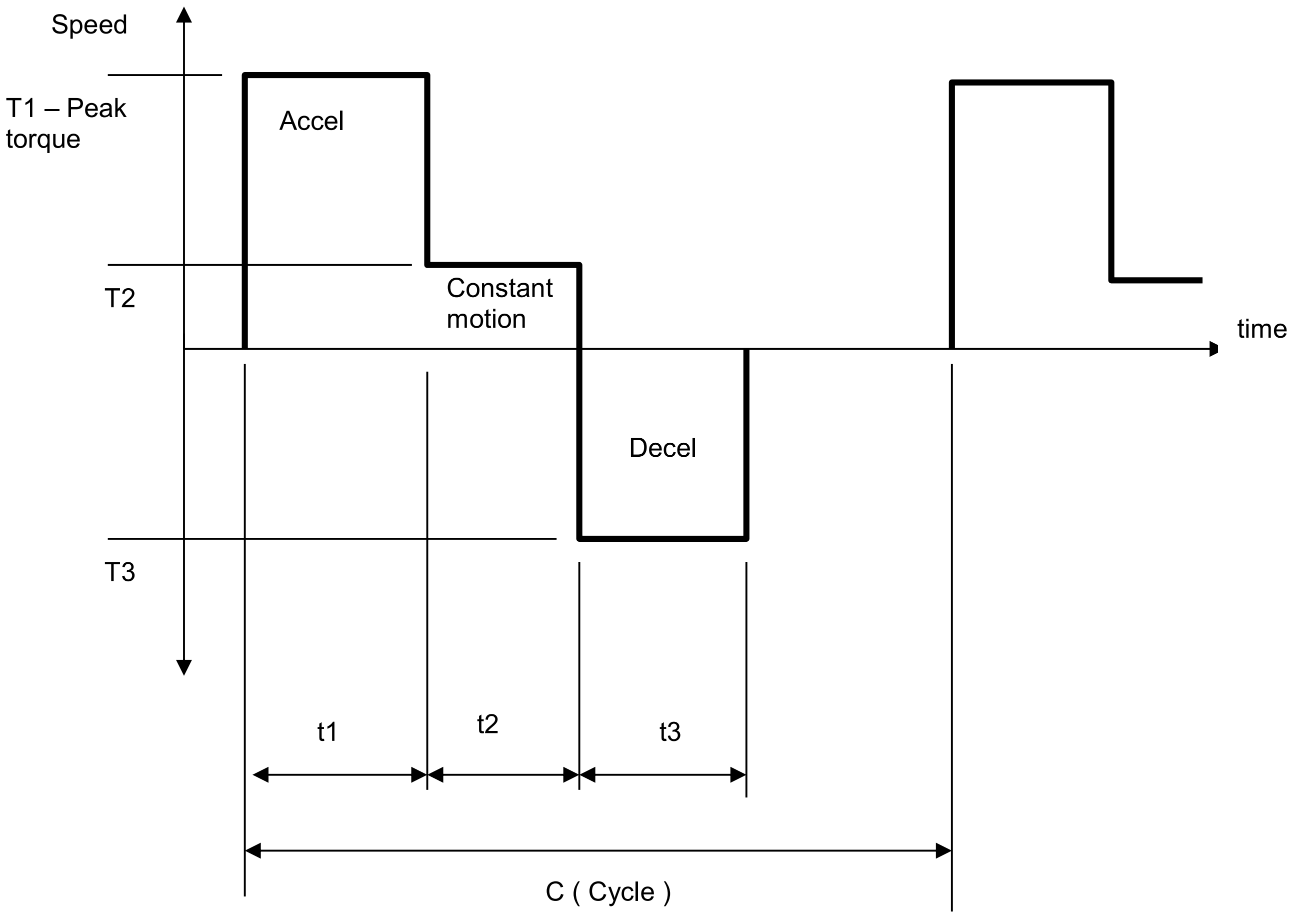
Before proceeding you must have the following **Torque / Speed Profile** data:-

- RMS torque – This must always be less than the continuous stall torque (Rated Torque) of the motor.
- Peak torque – Short time torque
- RMS current -
- Peak Current
- speed

Selection tip

We would advise all those involved with the selection to oversize their motor and drive packages by 30%. This will allow for extra loads, frictions and as well as any assumptions made during calculations.

3.1 Torque / Speed Profile



3.1.1 Torque RMS

$$\text{Trms} = \sqrt{\frac{1}{C} + T_1^2\, t_1 + T_2^2\, t_2 + T_3^2\, t_3}$$

3.1.2 Peak Torque

The short time peak torque of a brushless motor may be between 3 and 6 times that of the rated torque. It is important to ensure that the amplifier can deliver the current for this acceleration and that the motor can deliver the toque at the rated speed.

Selection Tip

It is usually safe to assume that the motor can deliver two times rated torque at rated speed. If you wish to get additional acceleration torque, study the motor torque curves and ensure you have accurate data for all the components of the calculations.

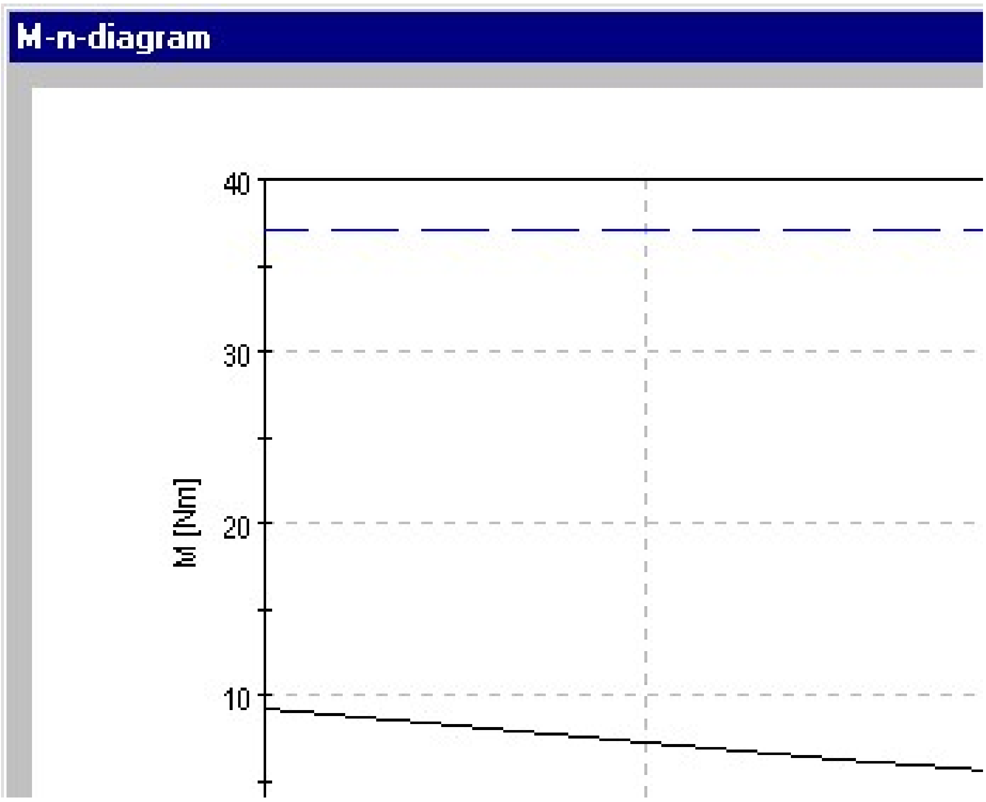
3.2 Motor selection

Using the manufacturers data sheets select a motor which is capable to providing the peak and RMS torques for your application.

3.2.1 – Motor Torque speed curves

Motor torque curves are published based on two major operating voltages. 300v for 220v amplifiers and 560v for 400v units.

Example – Siemens 1FK6 motor curve.



From the above example you can see the following interesting information :-

- Rated Torque is 3Nm at Rated speed of 3000rpm, but 10Nm at standstill.
- Peak torque at rated speed is limits to 18Nm rather than 37Nm.

Pulling more torque than is indicated by the S1 line (RMS torque) will result is the frame temperature of the motor increasing.

In some cases this motor might be labelled as a 10Nm, max speed = 3500rpm. This is true for SEM motors and can be confusing.

IMPORTANT

Once a motor has been selected, re-calculate acceleration torque with exact inertia of chosen motor.

Selection Tip

Motor carves have typically a 10 – 15% error tolerance and not always measured figures

Selection Tip

Some motors are rated in KW. To establish the torque of that motor
Power (Watts) = Torque (Nm) x Speed (radians / sec)

e.g. a 2 KW motor, rated @ 3000 rpm
2000 = Torque (Nm) x 314 radians/sec
Torque = 6.3Nm

3.3 Amplifier Selection

Once a motor has been selected with the correct peak and RMS torque figures, we then need to establish what amplifier to select. In order to do this we need to convert the torque figures to current. In many cases this is a published figure, alternatively it may be calculated using the Torque Constant of the motor (**Nm/Amp**)

From the above example curve, the torque constant is 1.28 Nm/Amp

For the 3Nm rating, we need (3 x 1.28) 3.84 Amps

If we had selected 8 Nm for acceleration we would then need 10amps, peak current capabilities

3.3.1 RMS Current

We now check to establish the RMS of the drive we require.

$$I\ rms = \sqrt{\frac{1}{C} + I_1^2 t_1 + I_2^2 t_2 + I_3^2 t_3}$$

3.3.2 Peak Current

Most amplifiers have a current limit which is twice that of the RMS current. In some cases amplifiers have additional peak capabilities.

Select an amplifier that can deliver the RMS and Peak current requirements.

Siemens MC drives

3 x Rated current for 250 ms, Cycle 1 s
OR
1.6 times Rated current for 30 s, Cycle 300 s

IRT 2000 / 4000 Series

2 x Rated current for 0.5

4 Mechanical Transmission

4.1 Pulley Reductions and Belt drives

Belts and pulleys are probably the most cost effective transmission mechanism.

4.1.1 Pulley

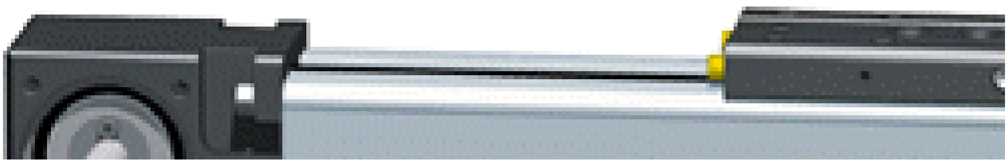
When selecting a pulley reduction the following points should be considered :-

- The maximum belt ratio we would advise for dynamic calculations is 3:1. Larger belt ratios require large distances between centres to ensure sufficient belt wrap.
- It is important to be aware of the effect of the pulley inertia in your total torque calculations. Never use steel, cast iron or other heavy materials.
- Keep pulley diameter to a minimum.
- Ensure correct wrap to transmit torque.
- Keep distance between centres to a minimum.
- Use taper lock fixings rather than keyway fixings.

4.1.2 Belt drives

Belt drives are a popular and low cost means of gaining linear actuation. We would recommend that the following points are considered.

- Use steel or Kevlar reinforced belts.
- Ensure pulley and belt can transmit torque.
- One long strokes ensure “ Snaking “ will not occur during acceleration.
- Use “S” shaped acceleration profile on motion control.



4.2 Gearboxes

When dealing with any gearboxes it is important to consider :-

- **Backlash** – This varies greatly between gearbox designs. This is typically expressed in arc minutes. There are 60 arc minutes in one degree. 21,600 in one revolution.
- **Transmission error** – This is best expresses as the speed deviation from a gearbox output for a constant velocity input. This can give errors of position within an output revolution. This is more common in worm gearboxes.
- **Torsional rigidity** – This is the wind up of a component when under a torque.
- **Peak torque loading** – Some gearbox manufacturers provide peak torque figures for their gearboxes. These figures should only be used for E_Stop conditions.
- **Efficiency** – Vary between design and also with age of gearbox.
- **Inertia** –
- **Life** – Gearbox life can vary between designs

Selection Tip

We would advise the use of planetary gearboxes for high dynamic applications

4.2.1 Planetary Gearboxes

Planetary gearboxes are the most commonly used gearboxes in the motion control market

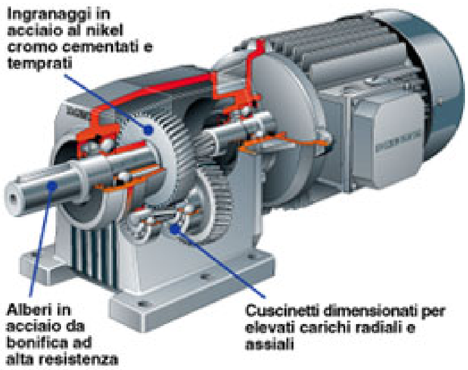
Backlash – Typically from 1 min arc to 25 min arc
Transmission error – Low
Torsional rigidity – high
Torque – High torque for physical size.
Efficiency – Typically between 90 to 98% for most planetary gearboxes.
Inertia – Low inertia
Life – Typically 20,000 hours at maximum continuous load.

4.2.2 Worm Gearboxes

Backlash – Typically from 20 min arc to 30 min arc
Transmission error – High
Torsional rigidity – high
Torque – High torque but large size.
Efficiency – Typically between 80 to 90% once run in. 60% is not uncommon for a new unit.
Inertia – Low
Life – Typically 2,000 hours at maximum continuous load.

There are some Servo Worm products available which rival the planetary gearboxes for backlash and transmission error.

4.2.3 Helical Gearboxes



Backlash – Typically from 20 min arc to 30 min arc
Transmission error – High
Torsional rigidity – high
Torque – medium torque but large size.
Efficiency – Typically between 80 to 90% once run in.
Inertia – High
Life – Typically 2,000 hours at maximum continuous load.

Again, industrial units not suited to high performance applications.

4.3 Screws

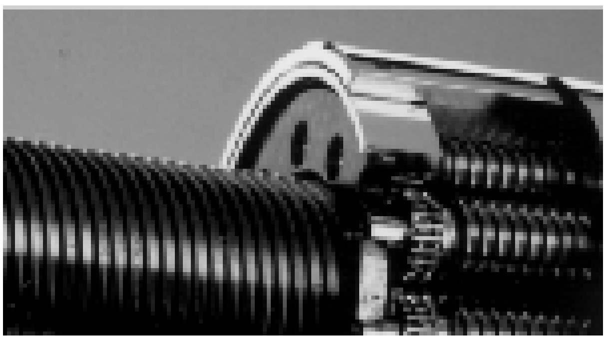
Screws are a very popular form of transmission. They provide a gearbox reduction effect to the motor shaft. We would suggest that the following are considered during design.

- Typical pitches are 2, 5, 10, 20 and 25mm
- At high rotary speeds the screw can whirl if unsupported.
- Are preloaded bearings required.
- What additional guides are required to support the load.
- What is the environmental exposure.
- Avoid driving the nut and having a moving screw, in such cases the nut can become a significant inertia.
- Screws are often provided with “ repeatability figures “. This is not the same as accuracy. This means that if repositioned to the same point on the screw the position will be within the repeatability figure.

4.3.1 Ball Screws

4.3.2 Roller Screws

Used in high load applications.



4.3.3 Acme Screws

Never use Acme screws in high performance applications. They suffer from poor efficiency and high backlash.

4.4 Couplings and Keyways

It is important to ensure that a quality coupling is used between gearbox / motor and the load. We recommend the use of servo couplings with clamp fixings.

If keyways are used to transmit torque in high performance applications, it is common to see key deformation and fretting. Ultimately this will damage the motor / gearbox.

4.5 Shafts

Most machines feature drive shafts. Consideration should be given to the following during machine design.

- Stiffness – is there any wind up in the shaft. Select larger diameter hollow shafts for a stiffer and low inertia shaft.
- Consider carbon fibre shafts to reduce shaft inertia.
- Can we mount motor nearer to avoid shafts.

5. Drive and motor fundamentals

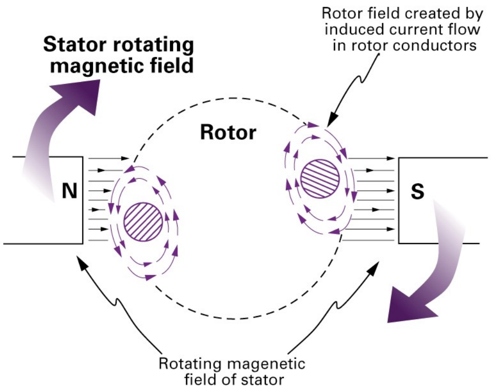
5.1 What is the difference between an AC and DC motor.

A motor is nothing more than a series of electro magnets. Passing an electric current, either AC or DC through coils creates an electromagnetic field, the resultant attractive and repellent forces between the field and armature causes the armature to spin.

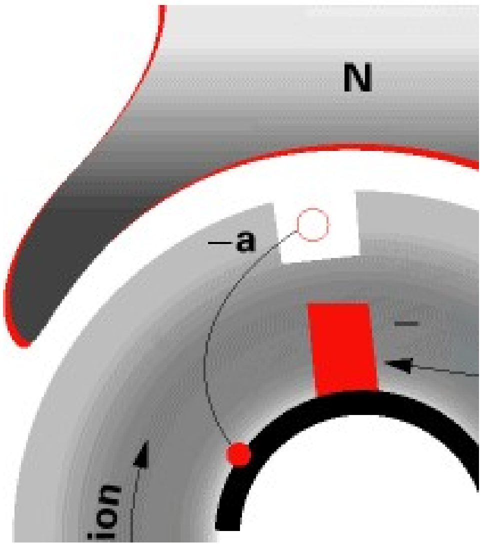
Magnetic fields tend to line up pole to pole, with like pairs repelling and opposite pairs attracting. If the current though one coil is alternated (directly, using AC power, or indirectly using a commutator) the polarity of that electromagnetic will reverse. This perpetuates like pole repulsion, causing the armature to spin. Simply think of this in terms of pushing two magnets together.

AC and DC motors both feature Fields and Armatures.

In an AC machine the Rotor (Rotary bit) is the field and the Stator (Stationary bit) is the Armature. This basically means that the current rotates on the outside stator and the rotor follows it.



In a DC machine we turn the system inside out. The Rotor is the armature and the Stator is the field. The current is switched in the Rotor causing the Rotor to seek the next pole pair, this causes the armature to rotate.



5.2 Brushless Drives

There are two principle types of drives, both are brushless, both are principally based on an AC motor model and both have a four quadrant output bridges. They are differentiated by the characteristics of the output bridge waveform and the construction features of the motors.

The two types of brushless drive are, Brushless DC and Brushless Synchronous, also known as Brushless AC.

5.2.1 Brushless DC drives

This is correctly referred to as a “ Trapezoidal back-emf motor driven by a Six Step drive “

The “ Six Steps “ refers to the six steps of commutation in one electrical cycle. The objective is to commutate (switch) the bridge electronically to keep the current flow in any particular motor winding flowing in the same direction.

The name “Brushless DC” is slightly misleading because the voltage supplied is AC not DC. The term arises because a brushless DC motor is similar to a brushed DC motor with electronic switches in the drive replacing the copper commutator and carbon brushes. Typically three Hall effect sensors detect rotor position and cause the drive to switch the supply to the motor accordingly.

Characteristics of brushless DC drives

Because of the crude nature of sensing and the switching in a trapazoidal waveform and as a servo motors have sinusoidal windings, this leads to torque ripple and cogging. Thus a brushless DC drives tends to be better suited to point to point positioning applications and not those where tight speed control is required. In addition the motor with hall effect sensors still needs to be fitted with an analogue or digital tacho to allow accurate speed control within the amplifier.

5.2.2 Brushless AC drives

This is correctly referred to as a " Sinusoidal back-emf motor driven by a sinusoidal current output drive".

This type of drive arrangement is very similar to that of a standard AC inverter. The current is phase locked to the rotor position, and the ampliftude, frequency and phase are controlled using PWM(1) signals to create a pseudo-sinusoidal output to the motor.

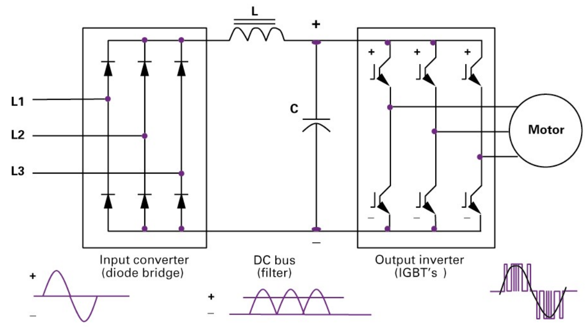
This solution utilises a synchronous motor. That is the rotor rotates at the same speed as the current phase, that is without slip. For the motor and drive to remain synchronised it is essential for the drive to know the exact rotor position. This is done by fitting an absolute encoder or resolver to the rotor and feeding this information back to the drive.

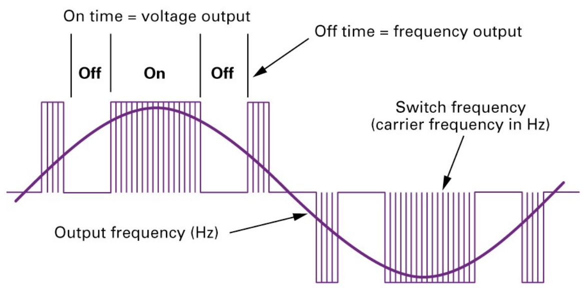
Characteristics of brushless AC drives

Brushless AC drives provide a very precise speed control and offer exceptional speed range. An advantage of using a resolver for rotor position feedback is that is also provides a velocity signal that can be used within the drive PID loop.

(1) **PWM – Pulse width modulated**

This basically is the switching of the drive output stage to simulate a sine wave. The frequency of switching is determined by the switching frequency of the drive. This is typically between 5kHz and 15 kHz. The diode bridge and filter create a smooth dc link voltage. By controlling each switch it is possible to apply either a positive voltage equal to the DC link voltage, or a negative voltage equal to the DC link voltage to the motor. This creates " Pulses " of positive and negative voltage. The drive controls the time each switch is on and thus "Pulse Width", so the average voltage is sinusoidal.





6. Conversion Tables

6.1 Torque Conversion

A \ B	N·m	dyn·cm	kg·m	kg·cm	g·cm	oz·in	lb·in	lb·ft
N·m	1	10^{7}	0.101972	10.1972	1.01972 $\times 10^{4}$	141.612	8.85074	0.737562
dyn·cm	$\times 10^{-7}$	1	1.01972 $\times 10^{-8}$	1.01972 $\times 10^{-6}$	1.01972 $\times 10^{-3}$	1.41612 $\times 10^{-5}$	8.85074 $\times 10^{-7}$	7.37562 $\times 10^{-8}$
kg·m	9.80665	9.80665 $\times 10^{7}$	1	10^{2}	10^{5}	1.38874 $\times 10^{3}$	86.7962	7.23301
kg·cm	9.80665 $\times 10^{-2}$	9.80665 $\times 10^{5}$	10^{-2}	1	10^{3}	13.8874	0.867962	7.23301 $\times 10^{-2}$
g·cm	9.80665 $\times 10^{-5}$	9.80665 $\times 10^{2}$	10^{-5}	10^{-3}	1	1.38874 $\times 10^{-2}$	8.67962 $\times 10^{-4}$	7.23301 $\times 10^{-5}$
oz·in	7.06155 $\times 10^{-3}$	7.06155 $\times 10^{4}$	72.0077 $\times 10^{-5}$	72.0077 $\times 10^{-3}$	72.0077	1	6.25 $\times 10^{-2}$	5.20833 $\times 10^{-3}$
lb·in	0.112985	1.12985 $\times 10^{6}$	1.15212 $\times 10^{-2}$	1.15212	1.15212 $\times 10^{3}$	16	1	8.33333 $\times 10^{-2}$
lb·ft	1.35882	1.35582 $\times 10^{7}$	0.138255	1.38258 $\times 10$	1.38258 $\times 10^{4}$	192	12	1

To convert an A unit into a B unit, multiply the A-unit value with the corresponding number listed in the above table.

Example: 100g·cm=100×9.80665×10^{-5}N·m
=100×9.80665×10^{-2}mN·m

6.2 Inertia Conversion

A \ B	Kg•cm^2	kg•cm•s^2	g•cm^2	g•cm•s^2	lb•in^2	lb•in•s^2	oz•in^2	oz•in•s^2	lb•ft^2	lb•ft•s^2
kg•cm^2	1	1.01972×10^{-3}	10^{3}	1.01972	0.341716	8.85073×10^{-4}	5.46745	1.41612×10^{-2}	2.37303×10^{-3}	7.37561×10^{-5}
kg•cm•s^2	980.665	1	980.665×10^{3}	10^{3}	335.109	0.867960	5.36174×10^{3}	13.8874	2.32714	7.23300×10^{-2}
g•cm^2	10^{-3}	1.01972×10^{-6}	1	1.01972×10^{-3}	3.41716×10^{-4}	8.85073×10^{-7}	5.46745×10^{-3}	1.41612×10^{-5}	2.37303×10^{-6}	7.37561×10^{-8}
g•cm•s^2	0.980665	10^{-3}	980.665	1	0.335109	8.67960×10^{-4}	5.36174	1.38874×10^{-2}	2.32714×10^{-3}	7.23300×10^{-5}
lb•in^2	2.92641	2.98411×10^{-3}	2.92641×10^{3}	2.98411	1	2.59009×10^{-3}	16	4.14414×10^{-2}	6.94444×10^{-3}	2.15840×10^{-4}
lb•in•s^2	1.12985×10^{3}	1.15213	1.12985×10^{6}	1.15213×10^{3}	386.088	1	6.17740×10^{3}	16	2.68117	8.33333×10^{-2}
oz•in^2	0.182901	1.86507×10^{-4}	182.901	0.186507	0.0625	1.61880×10^{-4}	1	2.59009×10^{-3}	4.34028×10^{-4}	1.34900×10^{-5}
oz•in•s^2	70.6157	72.0079×10^{-3}	70.6157×10^{3}	72.0079	24.1305	6.25×10^{-2}	386.088	1	0.107573	5.20833×10^{-3}
lb•ft^2	421.403	0.429711	421.403×10^{3}	429.711	144	0.372972	2304	5.96756	1	3.10810×10^{-2}
lb•ft•s^2	1.35882×10^{4}	13.8255	1.35582×10^{7}	1.38255×10^{4}	4.63305×10^{3}	12	7.41289×10^{4}	192	32.1740	1

To convert an A unit into a B unit, multiply the A-unit value with the corresponding number listed in the above table.

Example: 5g•cm^2=5×5.46745×10^{-3}oz•in^2