MOTOR Q&A

INTRODUCTION

We receive many enquiries for motors. Mostly general technical questions regarding the right choice of technology and motor family come up even before we start to talk about specific solutions. This white-paper is an attempt to address and provide answers to these questions and to provide the user with some guide-lines to making the right motor selection and MACON's rationale for MACCON's making the proposals we do.

Individually some of the comments and recommendations may seem trivial, however, in their entirety, these considerations can make the difference between a technically and commercially suitable electric drive system and a sub-optimum solution.

The most common questions relate to the type of electric motor to use and the possible mechanical forms available. This is where we will start.

There is one important restriction regarding the types of motor that MACCON sells and supports. MACCON's portfolio include all kinds of electric motors but NO combustion, hydraulic, pneumatic or piezo types!

TYPES

Servomotors and Torque motors

Servomotors are designed to provide high-efficiency (conversion ratio of electrical to mechanical power) at speed as well as good dynamic and positioning performance, accordingly they are long and have a relatively small diameter. The pole-count is usually low (typically 4, 6, 8 and 10). Servomotors are most commonly housed with position feedback and optionally with a holding brake.

Although servomotors are efficient in converting electrical to mechanical power, they should not be rated in kW. Often, we are asked to offer a servo equivalent to a general-purpose AC motor and are given the kW power rating from the type-plate. This mostly leads to the servomotor being over-dimensioned. The figures needed are the critical operating points (torque and speed) and the time and duty cycle for which they will be demanded.

Torque motors are designed to provide a maximum torque in a minimum volume and for a minimum power input, accordingly they are usually short and have relatively large diameters. The pole-count is usually high (typically 6 to >100+). Torque motors are most commonly frameless (stator and rotor kits); the user integrates these parts into the mechanical system himself, together with an encoder etc. as needed (see “Embedded Motion” below). MACCON’s torque motors are “brushless” and require electronic commutation for control; some families offer integrated Hall-effect sensors for this purpose (see below).

A selection of Servo- and frameless Torque motors

At stall their efficiency is 0% as there is no mechanical power output. Efficiency is the wrong term to characterize a good torque motor ; we use the term “motor-constant” instead (see below).

Direct Drive

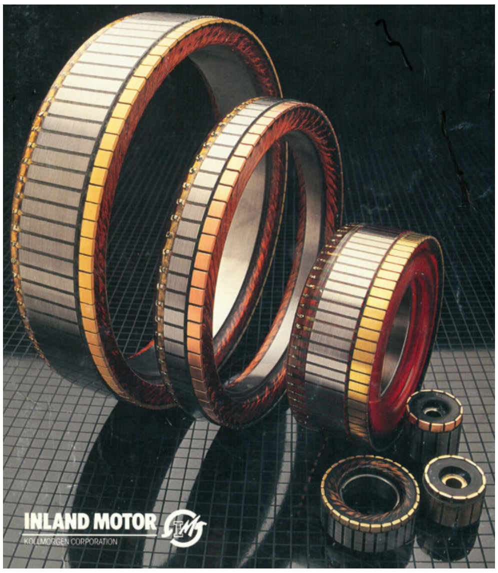
Torque motors are most always installed with a direct, stiff mechanical coupling to the load. No gear-box is employed; which is always a source of backlash (hysteresis) and resonance (due to limited torque stiffness of the torque transmission train). Direct drive has the advantage of being more accurate, more dynamic (higher bandwidth) and smoother at low speed (at the edge of stick-slip friction).

As a rule of thumb, it can be practical to achieve up to 10 times higher torque with a torque motor than with a servomotor, with much better control of the machine.

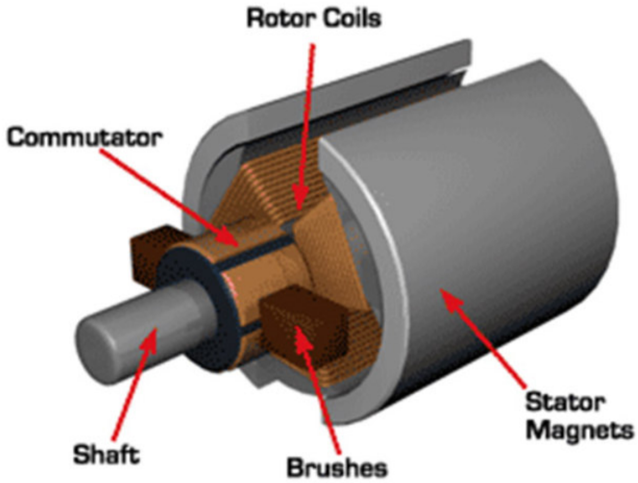
Linear motors are Direct Drive force-generating systems. Torque motors generate rotary torque and not linear force. Motor power output is either linear force (N) times linear speed (m/sec.) or rotary torque (Nm) times rotation speed (Rads./sec.; approx. 10 rpm).

DC brush motors

Traditionally servo- and torque motors were fitted with commutators and had only two leads; the supply voltage was direct and not 3-phase alternating, as for modern brushless motors. The winding (armature) is on the rotor and the outer stator is an iron ring supporting magnets and the brush assemblies. The brushes ride on a commutator mounted to the rotor. Rotation causes current to be switched from one winding to the next, synchronously with rotation; this change of excitation causes the magnetic field to and subsequently the rotor to rotate.



DC brush Torque motor rotors

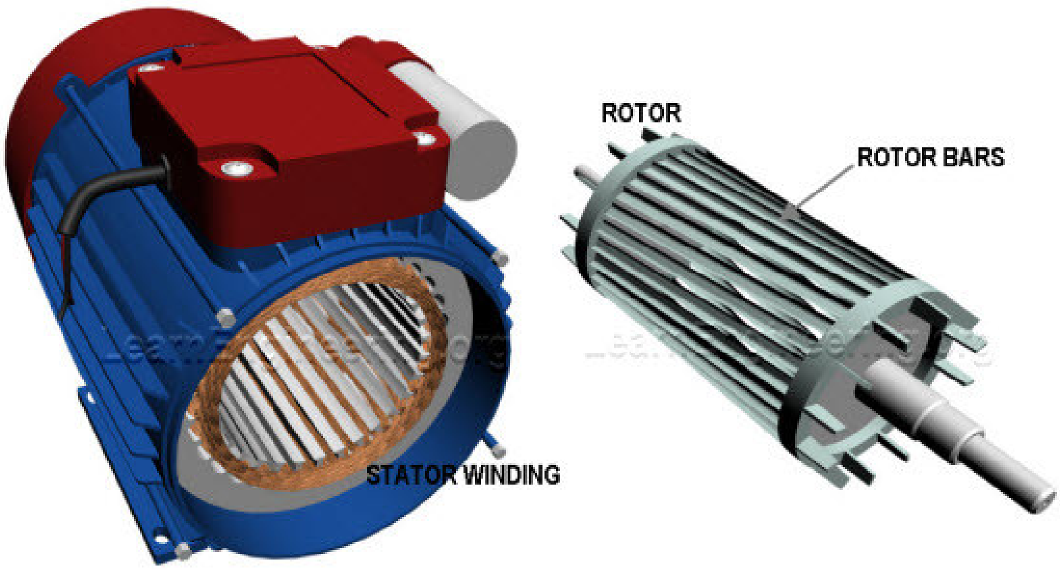


DC motor components

New DC brush motors are however no longer designed as this type of motor has a lower continuous and peak torque as well as speed; this is due to the mechanical commutation and the missing ability to change commutation angle with speed,

Induction motors

In the induction or asynchronous motor the rotor rotates more slowly than the AC excitation in the stator. The difference in excitation and rotor rotation frequencies allows field-generating current to be induced into aluminum or copper bars fitted in the rotor (so-called "squirrel cage"). The two big advantages are the possibility to drive these motors with no feedback, using cost-effective inverters, and the constant power characteristic (good for traction and material transport feeding applications).



Cut-away of an Induction motor, showing the "squirrel-cage"

The disadvantages are the lower efficiency and energy losses in the rotor (leading to larger, high inertia rotors). These motors are therefore seldom used for dynamic positioning servo-applications.

High pole-count AC motors also become very efficient, so they are not suitable for use a torque motors.

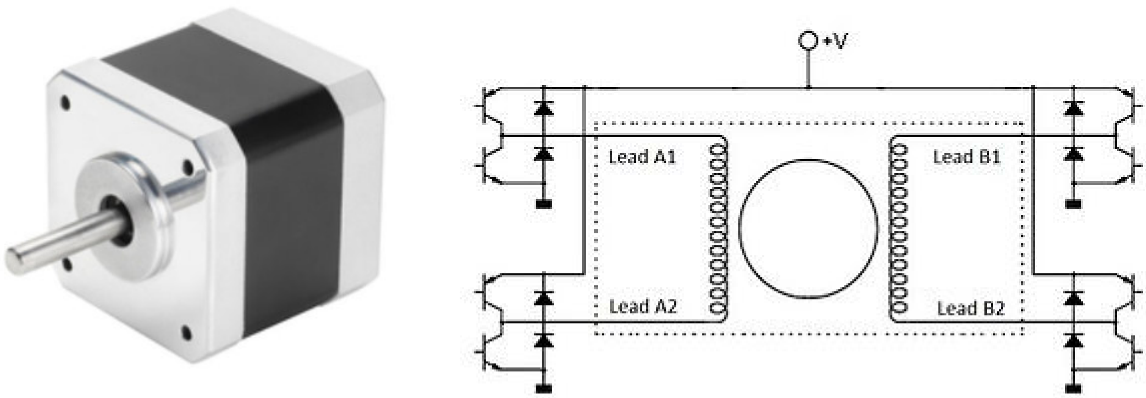
MACCON's focus is on synchronous motor technology. All other types of motor described in this paper are of the synchronous type.

General purpose motors (pumps, fans etc.) are usually of the AC, induction type. MACCON only offers this type of motors for special applications.

Stepper motors

There are different types of stepper motor but MACCON supports exclusively the 2 phase, 200-step hybrid version (hybrid because both reluctance and permanent-magnet field excitation are used). This motor has the advantage of having 50 pole pairs and therefore 50 preferential positions of magnetic attraction between stator and rotor, which cause the rotor to rest in one of these positions when the controller is switched off. This "reluctance" or holding torque is typically around 10% of operation torque, when excited. The motor can be made to position 200 full steps per revolution by sequentially reversing the currents in the two phases (+/+, +/-, -/-. -/+) with a 90° phase shift between them. As long as the load torque does not exceed the active holding torque of the motor, the user can follow the position of the shaft by simply counting the number of excitation-changes he injects into the motor.

A finer active control of position can be achieved with micro-positioning, whereby sine and cosine currents (in steps of 1/256 of nominal current or less) are excited in the two windings, allowing the rotor to take up any positioning angle (at zero load torque!). Other current modulation steps are common, half- and quarter step etc.

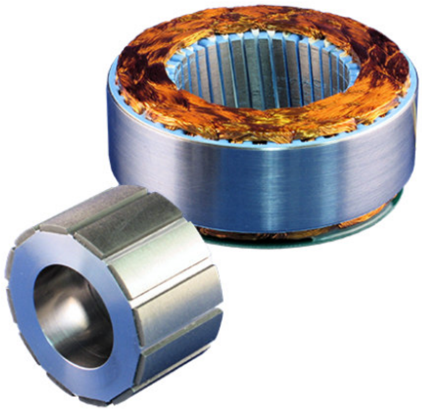


Stepper motor and winding/driver schematic (2 phase)

PM motors

The most common type of motor we sell, both of the servo- and torque types, are permanent magnet motors, with the magnets mounted on the outer surface of the rotor. This type of motor can have the highest torque-to-volume ratio and also a "square" torque speed characteristic (maximum torque available up to maximum speed).

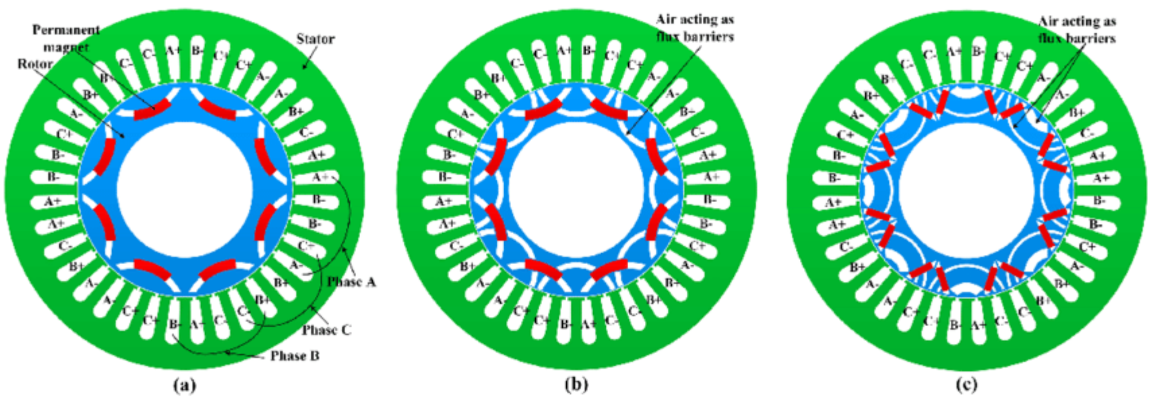
These are normally brushless (not DC brush) and driven by means of a controller, supplied by DC voltage. They are therefore called Brushless DC motors (BLDC).



PM, DC-brushless motor, showing rotor magnets

IPM machines

In the case of "interior magnet machines" the magnets are embedded in the rotor (the rotor now has to be laminated) with magnetic iron/steel between the magnets and the airgap. Field excitation is both PM and reluctance; its magnitude can be varied and therefore a constant power characteristic can be emulated (see "Field-weakening, below).

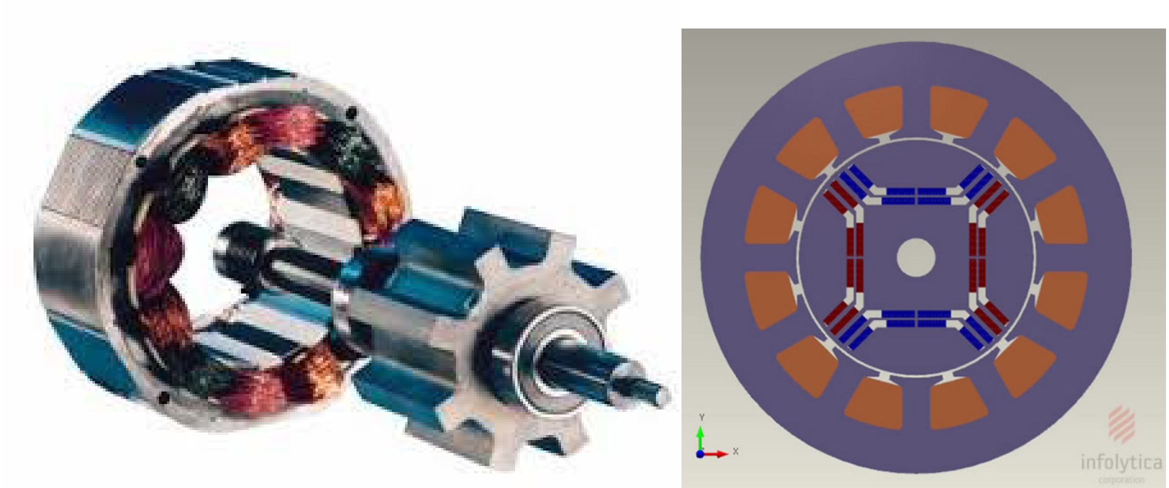


Cross-sections of different IPM machines

MACCON's traction motors are mostly of the IPM type (see below).

Reluctance motors

We offer two types of reluctance motors, Switched Reluctance (SR) and Synchronous Reluctance (SyR). Both have the advantage of having no field excitation without first being excited. This can be an important safety feature and allows for a constant power characteristic (see "Field-weakening, below). This property however means that these motors have a slightly lower efficiency than PM machines. The power factor is also much lower (high current ripple in the bus supply). As a result, a higher current rating of the inverter may be needed.



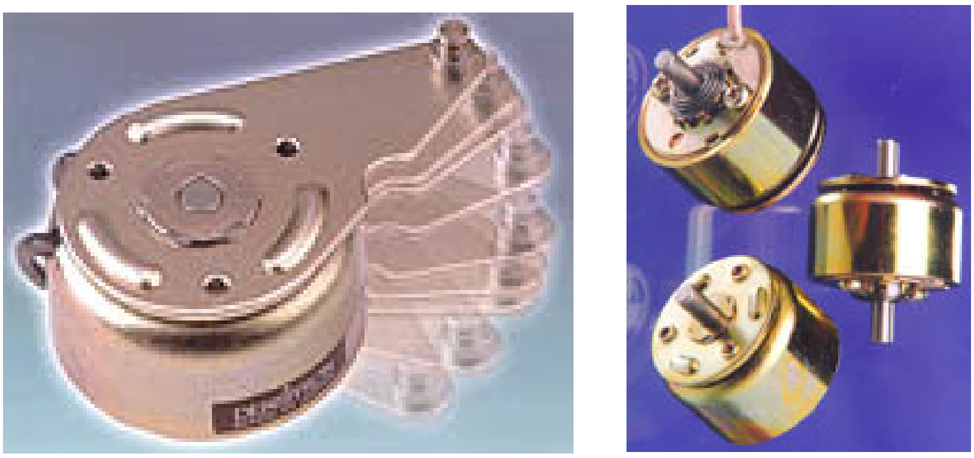
Switched (SR) and Synchronous (SyR) Reluctance motors (SyR as cross-section)

SR is however popular for mass applications, where robustness and low motor cost are important (well-known examples are the Thermomix from Vorwerk and the hand-dryers from Dyson).

Solenoids

These are simple electro-magnetic actuators, used for generating linear force over a short stroke (typically up to 50N over a few mm). As they operate solely on the reluctance principle, they generate force only in one direction, independent of the direction of current. They move between two extreme positions (bang-bang principle and normally require mechanical assistance to return to the unexcited position.

To avoid this limitation there are version with two independent coils, allowing bi-directional operation. There are also bistable versions with small permanent magnets to hold the end positions without the need to continuously excite one of the coils.



Solenoids for rotary and linear motion (G+)

Traction motors

Although MACCON'S traction Motors are similar in form to MACCON's PM servomotors. Their mechanical and electromagnetic design is optimized for high continuous power output; maximum operating speeds are typically 10,- to 12,000rpm. The high-power requirement involves good cooling; most traction motors are prepared for water-cooling. These motors are also commonly coupled with planetary gearboxes.

We also offer rim-wheel motors, which drive the wheel directly without gearing.

Power ratings are typically 1kW up to 250kW. Supply voltages (commonly battery) are 24, 48, 96, 150, 300, 400, 600 and 800V.

Various MACCON Traction Motors

FORMS

Housed motors

The standard expectation of the user is to purchase a motor, housed with through shaft and bearings. The motor is attached to the machine or plant, which it drives, via screw-holes or threads in the front-flange or it may be screwed to a machine base-plate via mounting feet. The motor output shaft is then connected to the load axially by means of a coupling or radially with the help of a gear-wheel or belt and pulley.

Frameless motors

A particular strength of MACCON is its portfolio of frameless motors. These consist only of stator and rotor rings; the user integrates these into his mechanical assembly, allowing for all ancillary parts: shaft and bearings, end-bells and flanges, encoders, brakes etc.

Torque motors are usually provided at frameless sets but we also recommend this design approach for servomotor applications (see "Embedded Motion" below).

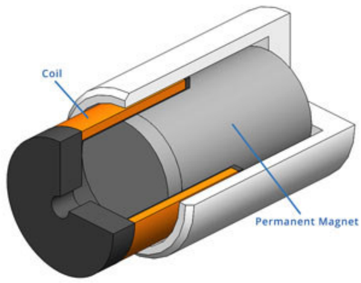
Frameless motor can be provided with inner or outer rotors. The inner-rotor type is most common as it is better for dynamic and high-speed operation; the stator can also be cooled more effectively. The outer-rotor type supplies more peak torque in the same dimensions and can be mechanically more convenient for the machine design (e.g. rim-wheel and direct drum drives).

Housed and Frameless brushless motors

Linear and voice-coil motors

MACCON motor technology can be equally be employed not only for rotary but also for linear motion. These are usually of the PM type, whereby the armature (coil) is usually short and the PM-track long; the coil is usually the moving part. Short-stroke linear motors can be voice-coil actuators, which only need a single-phase winding and a single H-bridge to drive them.

Ironless linear motors



Cross-section of a voice-coil

Occasionally the opposite configuration with coils the full length of the stationary track is employed (“long stator”) but this is either electrically inefficient or difficult to control. For short strokes this configuration is however common and has the benefit of needed no wiring to the moving part.

SPECIAL MODIFICATIONS

Windings

The selection or specification of windings is an art of its own. The simple rules are:

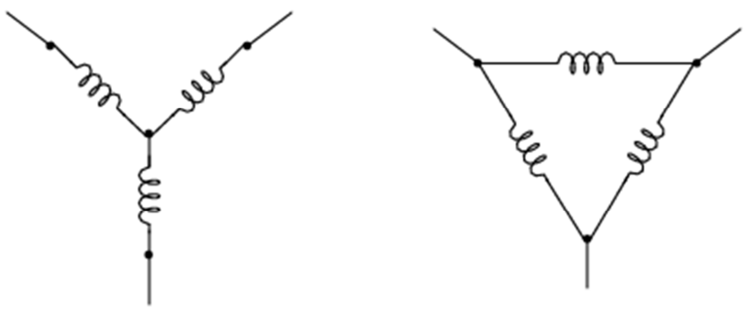
- Speed is limited by voltage (up to maximum mechanical and iron-loss boundaries)
- Torque is limited by current (up to magnetic and thermal boundaries)

- Windings can be chosen to allow higher speed for the same supply voltage, at the cost of higher current being required
- Motor size dictates primarily the continuous torque rating (NOT power output); voltage and current values can be chosen independently of torque by varying the winding
- Peak torque can often be many times continuous torque (RMS torque). It is only necessary to provide sufficient phase current and avoid overheating.
- Power is the product of speed and torque (10Nm @ 1,000rpm = 1kW)

The voltage, current, speed and torque are “trade-off” values, which can be optimized for a given continuous torque rating – with the help of winding selection.

Wye (or star) and Delta: 3-phase windings can be configured in two ways, wye or delta. Delta has the advantage that no internal central point connection is needed; this saves space at the end-windings. Delta is quite common for low voltage motors, where the risk of circulating currents (due to small phase in-balances) is low. The majority of MACCON’s motors are wound in the wye-configuration.

For a wye-windings it can make sense to make the central point accessible (4 lead configuration), this simplifies fault detection and location and can other advantages. It is also possible to exit both ends of each winding (6 lead configuration). This allows for the external configuration of wye/delta (1.73 speed ratio) or independent phase driving, for power or safety reasons.



3-phase motor winding configurations, Wye and Delta

In critical applications, both regarding safety and operational availability, we can implement winding systems; double, triple and quadruple systems are possible. These systems are implemented to minimize the possible electro-magnetic or electrical interaction between them in the case of failure.

Mechanical modifications

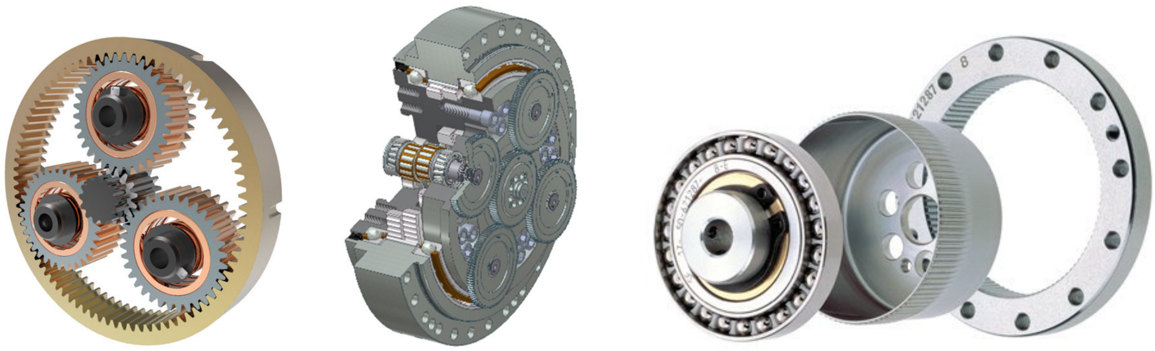
The number of possible mechanical modifications is uncountable. The most common requirement is to limit motor length (accepting a greater motor diameter if necessary) or to modify the shaft (flats and gear-profiles) and mounting flange (spigots, mounting holes, mounting and handling fixtures etc.).

Frameless motors can be implemented in two base configurations, with an inner or outer and rotor.

Gearboxes

When high power density at a low output speed is required, the servomotor is commonly coupled to a gearbox. This is also generally the most economical solution.

The most common gearbox type with good servo-positioning performance is the planetary gearbox with one stage (3 to 10:1 reduction ratio), two stage (15 to 100:1) or three stage (100 to 1000:1). Other types are the Harmonic Drive with no backlash (80 to 160:1 reduction) and light weight and also the Cyclo or Spinea types (50:1 or more reduction); the latter are very robust.



Reduction parts of planetary, cyclo and harmonic drive gearboxes

ENVIRONMENTAL CONDITIONS

Temperature

The performance of MACCON's motors is specified normally at a 25°C internal operating temperature. The internal insulation system of the motor is however limited to a maximum permissible temperature value (typically Class F 155°C, H 180°C, N 200°C, C 220°C). The continuous torque dissipation of the motor is limited by the temperature rise; i,e. for Class F insulation 130°C. As the internal temperature rises inevitably during normal operation, the effective torque rating of the motor falls. The peak torque capability is not strongly affected by rising temperature.

The predominant source of energy loss inside the motor is the resistance of the copper windings; the losses rise with the square of current (i.e. torque). In the case of a Class F motor the continuous available torque would drop by around 30%, when the internal stator-winding temperature rises by around 70°C.
Conversely these relationships mean that the better the cooling or the lower the environmental temperature, the higher the continuous torque of the motor. At high operational temperatures peak torque can still be available.

Magnets typically lose 0,5% magnetization per °C; this means that more current is needed to produce the same torque, as temperature rises. This effect is however mostly not as serious as the increase of winding resistance with temperature (0.004%/°C). This is because the rotor does not heat up nearly as much as the stator. For example, for a 70°C temperature rise the resistance of a copper winding increases by 30%. For applications with a low voltage reserve this leads to a reduction of the maximum speed achievable for a particular torque value.

Iron losses can also be significant at high speeds (depending on the lamination material and thickness); they typical grow with the third power of speed.

The lubrication in bearings and more seriously in gearboxes becomes increasingly viscous at temperatures lowers. Below -25°C this source of friction can rise steeply. For such low operational temperatures special grease must be used. This issue is critical, when the motor/gearbox is started at low temperature; once the motor is running friction drops quickly.

The heat losses generated in the motor must be dissipated. The standard channels for heat-dissipation are conduction to the surrounding structure through the front-flange and shaft, air-convection and some little radiation. Heat can be better dissipated by forced-air cooling around the motor body (ca. +30%) or by water-cooling (ca. +80%); water being forced through a water-jacket surrounding the stator.

Extreme Temperature & Radiation Conditions

Typically, the torque and power ratings of MACCON's motors are limited by the maximum permissible temperature within the stator winding (e.g. 155°C, class B insulation); the magnets and bearing lubrication may also present problems. At minus temperatures again lubrication, but also mechanical stress (differential expansion), cause problems. Accordingly, we normally declare -40° to +70°C to be the normal practical ambient temperature limits.

For higher operating temperatures class C insulation (220°C) may be used; for lower (<-40°C to -270°C) dry, non-grease lubrication is needed. At both extremes special material and manufacturing measures must be applied.

In projects for such critical and high-value applications it is common to perform extensive TV tests (temperature and vacuum). These tests are subject to charges.

In some critical applications (e.g. space and scientific) MACCON's motors can be subject to high levels of radiation. Normal PM BLDC motors can typically survive total (lifetime) radiation levels up to $10^{\wedge 6}$ J/kg (1 MGray). For higher levels (up to >50 MGray) special magnets and insulation materials must be employed.

Pressure, Vacuum & Outgassing

High pressure applications can mostly be found in underwater applications; these are particularly demanding on housed motors. Up to 100m depth (10 Bar) sealing can be achieved economically; deeper than 1,000m (100 Bar) or lower liquid pressure compensation is recommended (the motor is filled with inert oil and a diaphragm, allowing for pressure compensation with the external water – and thus no pressure differential across the bearing system, connector seals etc.).

In vacuum, semiconductor-manufacturing and space applications etc., outgassing can become an important issue – particularly for cooling and bearing/gear lubrication.

Further, the insulation and encapsulation materials used in MACCON's motors contain hydrocarbons, which can for example pollute semiconductor manufacture processes or the coating materials of optical systems. In such cases we use special materials and take special measures to minimize the quantities involved (target outgassing rates are typically TML <1 %, CVCM <0.1 % at <125 °C).

Shock and Vibration

Another big issue in extreme environments, such as vehicle and aircraft applications, is the mechanical robustness of the motor. Although electric motors are intrinsically robust, we are often requested to confirm that they will survive specified shock and vibration testing conditions, commonly to the MIL810G or DO160 standards. When test verification of the robustness limits is needed, non-recurring engineering charges (NRE) apply.

Dust, Moisture & Corrosion

Extreme environments also involve exposure to dust and moisture. Housed motors can be protected against negative effects of ingress according to the protection level. Categories of protection are defined in the IEC standard 60529, common levels are:

- IP00 No protection against contact and ingress of objects or water
- IP22 Protection against finger intrusion or similar objects and dripping water
- IP54 Protection against dust and splashing water
- IP65 No dust ingress possible, survives hosed water for 1 minute
- IP67 No dust ingress possible, survives water immersion, 1m deep

For IP65 and IP67 environmental conditions MACCON offers the "MSR" family of housed and ruggedized servomotors.

If special verification is required tests can be requested to the MIL202G and other standards. These tests are subject to charges.

A possible side-effect of moisture is corrosion; this can be on the outer surfaces of the housing or internal to the motor. Special materials and material treatments can be specified to avoid or minimize these effects (The MSR family offers a level of protection suitable for outdoor and vehicle-based use).

Sea and underwater applications present special challenges regarding pressure and corrosion-resistance. Special MgAl-alloys are used for the housings and the inside of the motor is either protected with pressure seals (at shaft and connector exits (for pressures up to 100 Bar) or the inside of the motor is filled with special oil, which cannot be compressed (thus neutralizing pressure differences across the motor housing and bearing seals).

EMC

A proven level of Electro-magnetic compatibility (EMC) is often demanded for MACCON's motors.

It is not possible to define EMC conditions for a frameless motor; the housing and grounding must first be specified. Even as an integrated housed motor, EMC can only be verified for a specified configuration, including the motor itself, housing, connectors, cables, inverter and line-filters, which have been assembled, mounted and earthed in a documented fashion.

In general MACCON's motors are highly immune against external EM emissions. The user is primarily concerned about emissions emanating from the motor that might disturb other equipment in his system or its environment. Here we differentiate between radiated and conducted emissions (transmitted via the connecting cables).

Screening and filtering measures can help counteract or attenuate EM emissions and improve system EMC. There are a number of EMC test methods, such as those specified in IEC-EN-61000 and MIL-461 standards. Such tests are subject to NRE charges.

POSITION FEEDBACK Options

Encoders

With the exception of the stepper type feedback devices must be mounted on the shaft of MACCON's motors in order to detect both positon and speed. For linear motors, linear feedback devices are required.

The most common and potentially most accurate type is the optical encoder. There are both incremental and absolute (single and multi-turn) types. Traditionally these encoders consist of glass or plastic discs with a printed position grid. On the one side is a LED light source on the other a photo-diode, which recognizes light modulation caused by the rotation of the disc. Other optical systems are now available, which make use of laser interferometry. Their resolution and accuracy are higher (up to 26 Bit per revolution or <100pm for linear movement).

Resolvers

Another common feedback device is the 2-pole brushless resolver, which operates magnetically and is absolute within 360°. This is a fully passive device and is highly robust. It is ideally suited to application with extreme temperature or vibration environments. A resolver is commonly integrated in servomotors.

Hall-effect Sensors

Position feedback devices are not only needed to monitor shaft position and speed but also to support the correct phase current commutation by the controller. Current commutation is needed to inject phase currents into the motor in order that maximum torque is generated. For 3-phase BLDC motors the minimum number of current steps in the 3 windings for a rotation of one electrical cycle (the pitch of two rotor poles) is 6. This can best be supported by simple Hall-effect devices, which are triggered by the rotating PM-poles on the stator. These devices can be easily integrated underneath the end-turns of the stator. The stator does not need to be lengthened to accommodate the HE-devices, only the rotor.

Other position feedback devices

There are many other types of position feedback, which use either magnetic or capacitive measurement principles.

These various feedback devices and their signal processing are not described here in greater detail (please refer to Google and Wikipedia).

AUXILLARY Options

Temperature sensors

It is common to integrate both temperature sensors in one or all three stator windings. These can be of the PT100, PT1000, PTC or thermocouples type (to actually measure temperature) or a bi-stable, opening switch (for temperature threshold operation, e.g. at 130°C).

This measure can be highly recommended for prototype systems. The sensor can be used to check the torque demands on the motor under true operational conditions in the actual application. Thereby the designer can be sure that he is not overdriving the motor or has not over-dimensioned it. Later the temperature sensor may not be needed (only a temperature switch may still be needed for safety purposes),

Brakes

It is common for holding brakes to be specified for use with servomotors. These can be provided already integrated in the motor. Most commonly these are friction pad brakes fitted with permanent magnets to attract the moving to stationary part. By exciting a coil, the magnet, attraction between the plates is neutralized, with the help of a small spring the plates separate and the torque of the brake is neutralized. Holding brakes are typically energized (released) by application of a 24V DC-supply. After release the voltage can be reduced to maintain the released condition (and to minimize energy dissipation in the brake).

Torque motors are normally supplied as kits; holding brakes have to be provided separately. Due to the flat geometry of the torque motor and it relatively large diameter, brakes of the disc type with brake calipers may give the best solution.

Dynamic braking: any permanent magnet excited machine can be braked under motion by short-circuiting its terminals. The braking torque is proportional to speed; this method is therefore not suitable for position holding purposes.

Cables

Cables are important part of a motor drive system. The cross-section of the conductors must be chosen support the continuous and peak currents needed. For low voltage systems particular attention must be made to the possible voltage drop over the cables as the specified operating conditions. This drop subtracts from the supply voltage and may become a cause of speed and/or torque limitation.

Many ancillary questions come up in connection with cabling: mating connectors (both at motor and at the inverter), screening, protection and bending radius

Controllers & Inverters

With the possible exception of DC-brush all MACCON's motors require a motor controller or "inverter" to operate. Typically these controllers include:

- 3-phase power stage, fed from a DC-bus (or AC with internal rectifier)
- Interface and signal conversion for motor feedback sensor(s)
- Phase current control, supported by "commutation" to ensure the correct distribution of the "current vector" between the phases.
- Torque, speed (velocity) and position control
- Interface to user host-control

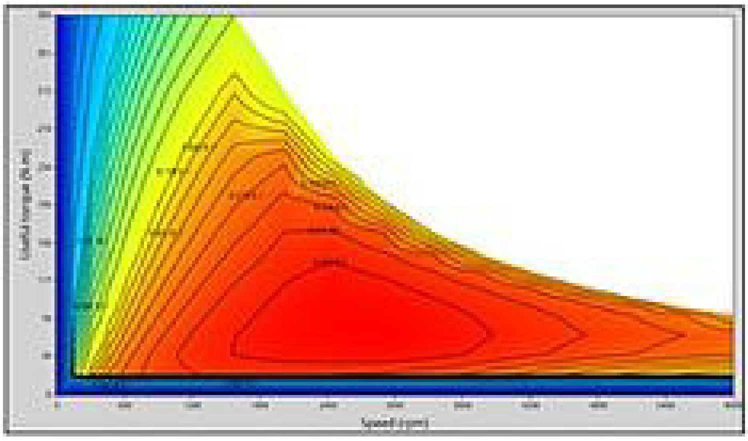
In this treatise the method of operation, functions and interface capabilities of MACCON's inverters are not described in greater detail.

Voltage drop: just as for cables this can be critical for low and (medium voltage applications) It should not be forgotten that IGBT-based inverters may have up to 8V voltage-drop over their output stage. This voltage-drop is less critical for MOS-FET output stages but this voltage loss is linearly proportional to current and should also not be ignored.

IMPORTANT PROPERTIES

Efficiency & Torque constant

As mentioned above these two terms are important to characterize the capability of a motor to generate mechanical power OR mechanical torque; whichever one is important depends on the application.



Motor efficiency, shown against torque and speed (red is highest!)

Cooling

The main performance limitation of a torque- or servomotor is not the peak torque but the continuous (effective/RMS) value torque. This value depends strongly on the cooling provided. In the motor datasheet a continuous torque value is normally given for conduction cooling to a typical machine structure supporting the motor. This value can be improved with forced air-cooling across the motor body (typically +30%) or water-cooling through channels in a housing directly surrounding and in contact with the stator (typically up to +100%).

Make allowance for the fact, that with increasing environmental and internal operating temperature the available continuous torque value reduces (see: “Temperature” above).

In practice, one should never assume an effective peak-torque value higher than 3 times the continuous torque rating of the motor.

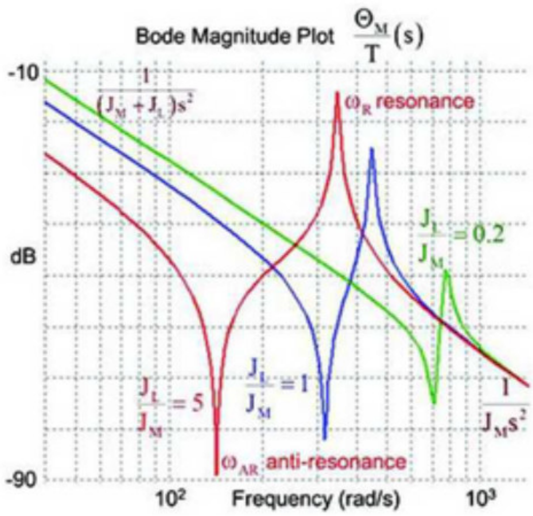


Figure 1: Factors like inertia ratio change the frequencies of resonance peaks, making it possible to better flatten the gain curve. *(Courtesy of Kevin Craig, Hofstra University)*

Bode plot indication of the effect of inertia mis-match

Accuracy

There are many alternative interpretations of the word “accuracy”. The user should clearly differentiate between the absolute accuracy and resolution required. Position repeatability is +/- 1 bit; this is the usual interpretation of accuracy.

Typical resolutions of MACCON’s resolvers and encoders start at 12 bit and may go up to 26 bits for highly precise systems.

Absolute accuracy, which must allow for mechanical precision errors of manufacture and assembly as well as temperature, may be 4 bits lower than the resolution. However, with good assembly and calibration; an absolute accuracy closely equal to repeatability is achievable.

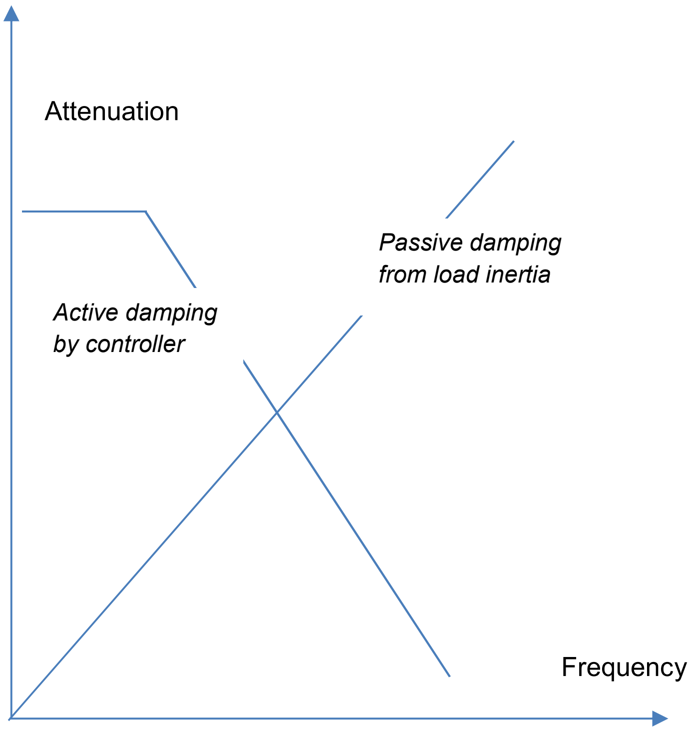
Dynamic Response & Smoothness

Load acceleration and deceleration are limited by the peak motor torque available and the inertia (motor + load). Static load torques (friction + vertical mass support) as well as reaction toques from the tool and workpiece subtract from the peak torque available from the motor itself.

Dynamic response can have a further significance. A wide bandwidth is not only needed for high acceleration but also to reach the target position quickly and to control smooth, slow motion (against load disturbances and bearing stick-slip effects).
A high feedback resolution is also important for both target position accuracy and good axis control damping.

Oscillating applications: this kind of dynamic application can be one of the most demanding. The maximum achievable stroke is inversely proportional to inertia (motor + load) and the RMS torque or force of the motors. The maximum operating frequency is inversely proportional to the square of this RMS value.

High load inertia can however be beneficial for smooth motion; it automatically damps disturbances; the damping effect automatically increases with frequency.



System Damping (Closed-loop bandwidth, controller load inertia effects)

The critical disturbance frequency range, where neither the active servo-control loop nor passive inertia damping compensate, is between a few and 100Hz depending on the mechanical configuration.

Both dynamic response and smoothness can also depend on the stiffness or "eigenfrequencies" of the load structure or the torque-coupling path between the motor rotor and the load. If these natural (eigen-)frequencies are excited load control suffers (both positioning time and smoothness suffer).

Backlash in the gearbox can cause a similar effect. As a rule of thumb, the reflected inertia of the load back to the motor should not be higher than 3 times rotor inertia in order to avoid such serious resonance problems in the gearbox.

Direct drive systems (torque motors) have a key benefit. The coupling between rotor and load can be made extremely stiff with zero backlash! Direct drive offers the best servo-control of all drive systems.

If the eigenfrequencies are known or can be established by practical tests, there can be another way to avoid these negative effects. Do not excite them, i.e. do not inject torque commands into the motor at these critical frequencies. Use an S-curve acceleration ramp, which may not contain such frequency components. Remember that a linear velocity ramp or a torque command step includes many harmonics (analyze not just the base frequency of the command signals but also all higher Fourier components).

Notch-filters in the position control loop maybe an alternative way to avoid this problem.

Cogging & Damping

MACCON's PM motors usually exhibit cogging torque. This is because the stator has iron teeth, which are directly attracted by the permanent magnets on the rotating rotor, independently of stator excitation. The order of this disturbance torque component is typically around 1% of datasheet peak torque. Cogging can be reduced up to one third by increasing the airgap between stator and rotor or skewing the stator but torque and motor constant suffer from these measures.

Cogging is of no disadvantage for dynamic or positioning applications; high cogging motors generally have a high torque for their volume and can thus be at an advantage. When positioning or at low speed the disturbance effect of cogging is compensated by the closed-loop gain of the controller. However, when motion is required at motor speed matching a frequency range with low damping (see figure above) or can excite structure eigenfrequencies, motion quality may be impaired.

The disturbance frequency normally matches the electrical frequency of the motor (rpm x number of poles/2) or its third harmonic.

There are PM motors with no cogging; in this case the stator iron is symmetrical with no "salient" structure. The copper winding is mounted on the stator in a relatively large airgap. The motor constant is considerably lower than for a conventional stator with iron teeth but the motor runs smoother and faster (eddy-current losses in the stator are also lower)

Damping (magneto-strictive friction, which is proportional to velocity, independent of motor excitation and caused by magnets moving relative to iron) is also lower for airgap wound ("ironless" motors. There is one type of "ironless" motor, which has zero damping and cogging; in this case the stator is a copper winding without back-iron; the back-iron rotates with the permanent magnets mounted on the rotor.

Damping is not per se a disadvantage; it may help to stabilize control, along with active damping provided by the control loop.

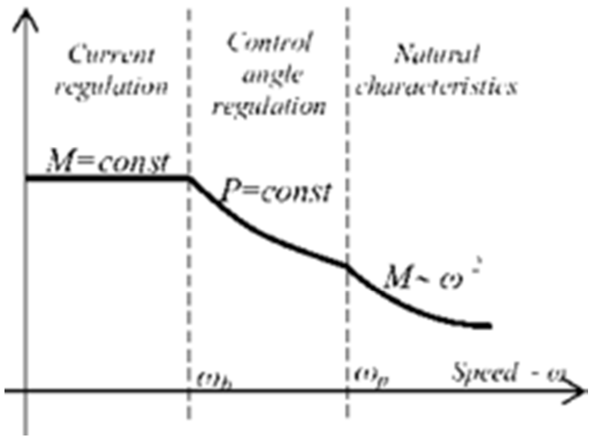
Regeneration

All of MACCON's motors can operate in 4 quadrants. This means they can be controlled to provide positive torque in a forward direction (acceleration); negative torque in a forward direction (deceleration or braking) or negative torque in a negative direction etc.
The condition of negative torque implies removing mechanical energy from the rotating rotor and load. This leads to electrical energy been returned to the supply. The supply is usually the output of an AC/DC-rectifier or a battery. A rectifier will not allow current to be fed back to the AC source; capacitors and batteries will accept only a limited amount of energy until voltage rises to an unacceptable value or damage occurs. Measures must therefore by taken to absorb or otherwise dissipate the excess energy. The solution is usually to switch a resistor load across the DC supply bus, once the voltage reaches a critical level. This is known as regeneration protection.

In other words any of MACCON's electric motors can also be used as generators (or both: "starter-generator").

Field-weakening

AC and reluctance machines have no magnets. The inverter can therefore control field-excitation from zero. This means that speed may not be limited by the supply voltage. Typically, an operating curve (torque vs. speed) of constant power results. The user can dictate maximum speed by means of the inverter control parameters.



Motor torque/speed curve with field-weakening

This also means that unless negative torque Is commanded there is no regeneration. This can be important in some applications, e.g. for safety reasons.

Some PM motors, particularly the IPM machine however do allow for the Permanent-magnet field to be reduced by modulating the excitation current, in order that one phase component, "Id" generates a field component opposed to the PM-field ("Iq" I the torque producing component of the phase current). This means that the motor can run faster than with normal excitation (the torque output however reduces with speed). By means of this approach a constant power range of up to around 3:1 is often possible.

An advantage of field-weakening is further that less phase current is needed to produce high torque at low speed. A disadvantage is that high back-EMF values are possible at high-speed, when the inverter fails or disabled. In this case high energy may suddenly be released back to the power supply and uncontrolled braking torque can result.

MACCON propagates a variation of the field-weakening approach – FSW, Field strengthening or weakening, “Id” can now be either positive or negative. This requires more current from the inverter; less however than with no field-weakening capability but uncontrolled regeneration can be avoided. Typically, a 2:1 power range can still be achieved (the maximum inverter current also being reduced by a factor of 2).

EMBEDDED MOTION

Last but not least we want to recommend the Embedded Motion design approach, whenever this makes sense. Embedded Motion is a technical approach to building machines which can then be less expensive, more mechanically and electrically efficient.

Think about it like this: if you need to drive a shaft inside your machine which has its own bearings and housing, why use a housed motor, which in turn has its own bearings, own shaft, own housing ? It makes more sense to use a frameless motor (a.k.a. "kit motor"). In this case the rotor drives the machine's shaft directly. There is no unnecessary coupling between a motor shaft and the driven shaft. The stator is attached directly to the machine's own housing. In doing this we save cost, weight and space. Not only that, we improve the mechanical qualities of the machine by eliminating the coupling normally required to connect the motor shaft to the driven shaft. Electrical power consumption is reduced, as the motor only has to overcome the friction of the machine's own bearings. All of these arguments apply to either rotary or linear motors (see images on the right hand side). As well as the motors, linear or rotary encoders can also be supplied in kit-from, for direct integration into the customer's machine. Last but not least, the drive electronics can also be installed inside the machine.

This approach applies equally to rotary and linear motors.

The economic benefits of embedded motion can be summarized as follows:

- Lower material cost (save two bearings, one shaft, one coupling and one motor housing).
- Motor takes up less space and weighs less.

- The machine shaft is shorter and no longer comprises two parts. It is stiffer and has less inertia. This makes the machine more dynamic and eliminates unwanted resonance frequencies.
- The thermal cooling of the motor can be optimized. Heat dissipation from the motor is directly into the machine structure, which normally represents a good heatsink.
- The motor's drive electronics and the machine's control electronics can be integrated onto the same circuit board.
- By integrating the electronics into the machine, cable lengths can be made shorter and connectors can be eliminated. All of this saves cost, and, improves EMI/EMC characteristics.
- Some machines with special geometrical and weight requirements simply could not be built without applying the principles of embedded motion.
- Costs are also reduced by eliminating unnecessary installation steps.