# Precision Machine Design-Actuators

Actuator is the source of power and drive, thus it plays a key role in design of precision machine system. Factors such as range, resolution, repeatability, and thermal characteristics are important features to consider. Electric servo motors, linear servo motors are considered. Electro-magnetic actuator and piezo-electric actuators are also considered for the small range.

1. Electric servo motor

The size constants are the motor parameters, being independent of winding, they are;

Maximum stall torque [Nm]: The maximum stall torque (peak rated torque) is defined as the torque that produces a specified winding temperature rise in a given time with the motor shaft locked and no external cooling or heat sinking

Tc, Continuous stall torque[Nm]: The torque results in a specified steady-state temperature rise. A motor can operate continuously at this stall torque in a specified ambient temperature

Maximum continuous output power [W]:The maximum shaft output power that can be obtained from a specific motor without exceeding a specified steady state temperature rise

$K_M$, Motor constant[Nm/W$^{1/2}$]: Ratio of peak torque to the square root of power input at stall and at a specified ambient temperature. $K_M$ indicates the ability of a motor to convert electrical power into torque

TPR, Temperature rise per watt [℃/Watt]: Ratio of temperature rise in winding to average power dissipated from the armature

$F_0$, Damping coefficient [Nm/rpm]: Torque loss due to rotational losses, mainly due to eddy current which is proportional to speed. This is a kind of friction effect.

$T_F$, Hysteresis Drag Torque [Nm]: Magnetic friction due to hysteresis in armature laminations, includes the cogging torque. It can be decreased with larger air gap and higher efficient laminations, but with disadvantage in performance when air gap increases.

Cogging torque[Nm]:Torque resulting from the alignment magnet and lamination tooth edge. This is the torque experienced when a motor is rotated by hand, and

-it is the major cause of control problems at low speed.

–it can be minimized with the use of slanted windings and the increase of air gap

-can be minimized with the use of sinewave controller triggered by the hall effect sensors

-can be minimized by increasing the number of poles

Winding constants

: motor parameter depending on winding, thus it changes in different winding

Tp, peak torque [Nm]: Peak torque when the peak current(Ip) is applied to the motor such that $Tp=K_T Ip$

Ip, peak currect[A]: Current obtained when the voltage is divided by terminal resistance of motor such that $Ip=V/R_M$

$K_T$, Torque sensitivity [Nm/A]: Ratio of torque developed to armature input current. Thus when current I is applied, the torque, $K_T I$ is always developed whether the motor is running or stationary.

No-load speed [rpm]: Operating speed of motor with no load. It is obtained from the applied voltage divided by $K_B$

$K_B$, Voltage constant [V/rpm]: Ratio of voltage generated in armature to the speed of armature, $K_B$ and $K_T$ are proportional.

$R_M$, Terminal resistance [Ω]: Resistance between the two terminals of motor.

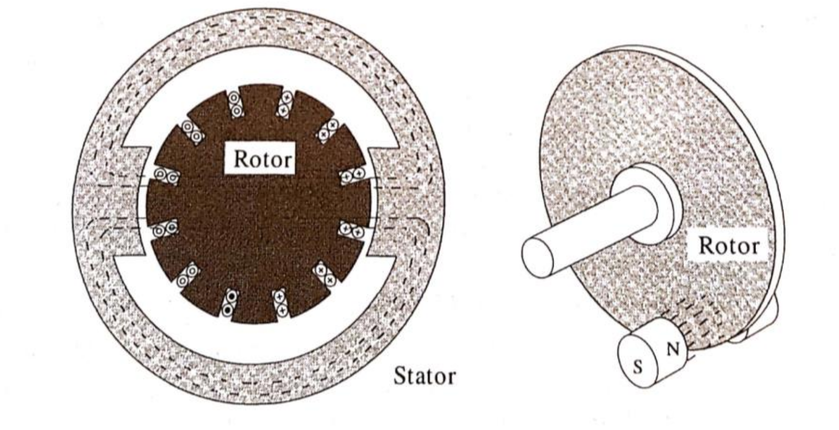
$L_M$, Terminal inductance [H]: Armature inductance measured at the motor terminal.

Maximum continuous output power[W]: Maximum shaft out power obtained from the winding at the stated voltage without exceeding steady state temperature rise.

1) DC brushed servo motor

Stationary magnetic field is induced in the stator's coil with DC current; a rotating filed is induced in the rotor's coil with DC current transferred to the rotor winding via brushes making contact with a segmented slip ring on the rotor. Rotor and stator' fields try to align with each other. When the rotor rotates then magnetic fields come to alignment, the brushes move onto a conductor for a next set of windings, so the magnetic field are misaligned again, and hence the rotor continues to rotate to try new alignment.

Various configurations for stator and rotor windings, and radial pole and axial pole windings are typical as in fig.




DC brushed motors: radial pole type and axial pole type

(source: Slocum's precision machine design)

For radial pole type (or iron core) type motor, a left end point on the rotor experiences force in the tangential direction (upward) from the Fleming's left hand rule for motors, because stator magnetic field is developed from left to right, current flows from back to front. Thus the rotor can rotate in CW direction.

Similarly, for axial pole type motor, a bottom point on the rotor experiences force in the tangential direction (from left to right) because the stator's magnetic field is from front to back, current flows radially downward. Thus the rotor can rotate in CCW direction.

For the axial pole type motor, there is no iron core, rotor inertia can be greatly reduced, and the cogging can be eliminated because the number of current flowing paths are large.

For the radial pole (or iron core) type, there will be sinusoidal variation in torque due to a limited number of windings on the rotor(armature). The more slots (or windings), the better for reducing cogging. Slanting the armature's windings, thus making a helix windings can give a solution for reducing cogging, but it may make extra cost for manufacturing and heat generation increased. Cogging can be reduced by increasing the air gap, but resulting in reduction of torque and efficiency.

Advantages of brushed DC motor:

-Simplicity of operation that requires only power supply for voltage and current providing, power OP amp, analog output from the servo control algorithm (controller)

-Inherent braking ability, in which the braking action is achieved by disconnecting the armature from the power supply, then connecting the leads together. The rotor are still rotating, then motor becomes generator, and the currents generated in the armature creates the magnetic field opposing motor rotation. Thus no power input, no heat generation is required for the braking.

Drawbacks of brushed DC motor

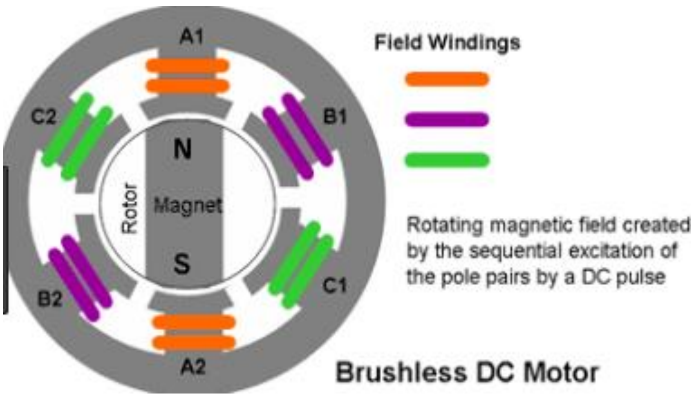
-The brushes wear off and small particles generated, or it can burn out under high torque or high current condition

-Windings on the rotor will generate heat by the resistance of the windings. The generated heat can be conducted to the lead screw as the major heat source

-Small sparks are generated at the brush interface, and it can make the DC servo motor unsuitable for use in explosive environment.

The power OP amp based DC power supply is commonly used, but it can dissipate and generate large heat. The PWM (Pulse Width Modulation) can be alternative, where a constant voltage power supply is used with pulsed power train of high frequency by a switching power supply. The switching power supply accepts a signal from servo-controller to make the proportional width. Thus power dissipation can be in the form of radio waves, so that components do not burn out like heat dissipation. The torque output of the motor is proportional to the width of pulses, typically of 3KHz, for machine tool applications. For submicron resolution machines, small vibrations of this frequency range can cause vibration issue, thus more higher switching power frequencies can be used. In this case, however, other electronics nearby can be disturbed with noise, because even short length of wires can act as antenna easily due to the wave of higher frequency, or shorter wavelength.

2) DC brushless servo motor




(source: electropaedia)

The magnetic field of the rotor is provided by the permanent magnet without any current input to the rotor through the brush. Hall effect sensors (or resolver) located in the stator give a signal to the motor driver when to switch the current in the stator's windings to create the rotating magnetic field for the rotor. Thus heat generation is mainly from the stator windings, and it is dissipated through the motor housing, thus can be cooled or isolated thermally easily, and very little heat generation is coming from the rotor that directly connected to the lead screw. Very small velocity with high torque running is possible without high temperature rise due to the brushless configuration. Discrete number of permanent magnets in the rotor, however, will generate sinusoidal variation, or cogging, to the torque output. The PWM drivers are also widely used for the brushless servomotors. In order to have cogging torque mapping or correction with digital electronics, DSP(Digital Signal Processor) based servo controllers are also frequently used. The brushless DC servo-motor are widely used in machine tools, robots, and inspection machines, because it can provide very high torque in a small space with very little heat generation, although with relatively higher cost than the DC brush servo motor.

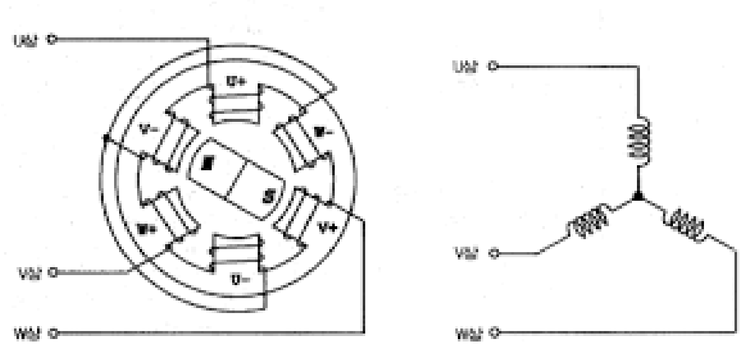
Drawbacks of the brushless DC servo motor:

-The rotor magnet can be demagnetized under high currents, other strong magnet field, or high temperature, although these factors are not so serious in general factory environment. Care must be taken in assembly or in service for the motors, because the permanent magnet of the rotor are extremely strong and brittle.

-The cogging can be compensated by using the sine wave driver, but it costs high; and the square wave driver of lower cost has limit in minimizing the cogging torque.

-Braking can be implemented by reversing the current input to the windings (stator), requiring almost the same power as for running. This is not a big issue for axis moving, but it is better to be avoided for high speed spindles or main spindles where power usage and heat generation are critical.

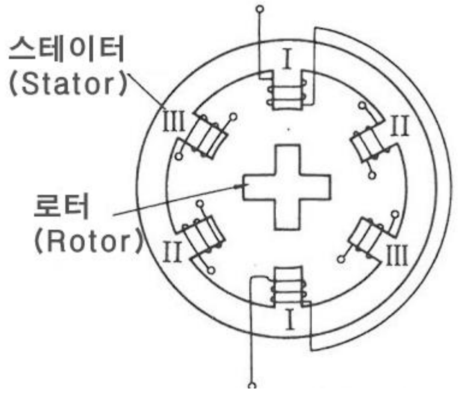
3) AC induction servo motor (or AC servo motor)




(source:www.cnasystem.com)

In an AC induction servo motor stator, two out of phase sine waves are input to the two stator windings, that causes a rotating magnetic field to be established. Conductors on the rotor are at right angles to the magnetic field, and it causes current to be induced in the conductor. The induced current in the rotor causes in turn a force to push the conductor out of the field, thus to rotate the rotor. Torque is proportional to the amplitude of the sine wave and the speed is limited by frequency of the wave. The rotors lags behind the sine wave, and its motion is asynchronous. The AC induction servo motor is the simplest and most rugged types of motor. Discrete number of windings in stator and conductors in the rotor also generate the cogging torque, and some heat is also dissipated in the rotor conductors. Due to low cost and simple configuration, this motor is widely used for high power motors such as power spindles, although they must be braked by reversing the current in the stator windings.

4) Stepper motor

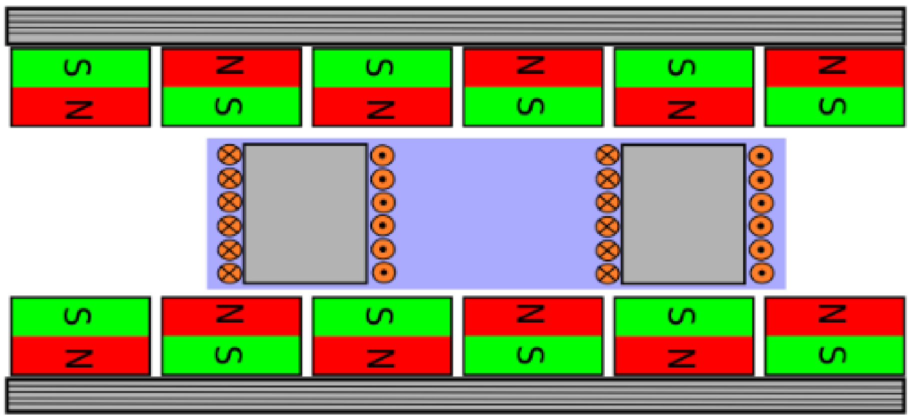



(source:http://blog.naver.com/PostView.nhn?blogId=motorbank01&logNo=100164167469)

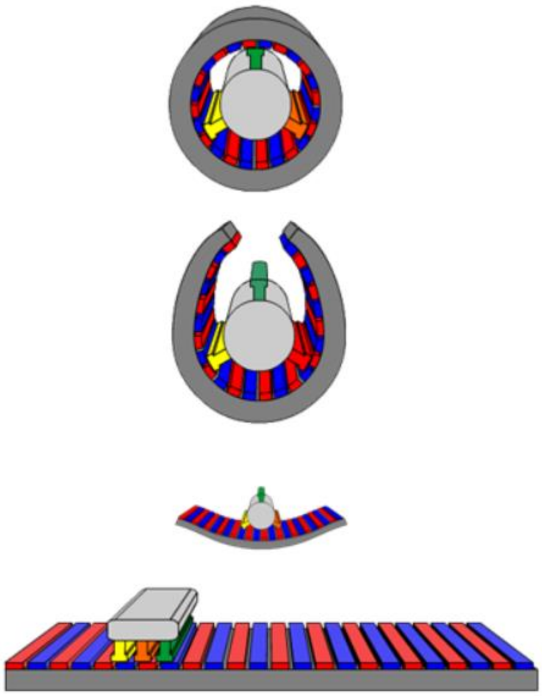
Stepper motors are synchronous motors that use a motor driver to control the rate of rotating magnetic field and keep track of field position. The rotor position is known without the use of a feedback sensor. The step angle is determined by the design of the motor and driver, typically few degrees, or few mili-radians with advanced drivers. The step motors are widely used in index tables, conveyors, printers, etc. due to cost effectiveness and simple configuration without feedback sensors. For machines in need of contouring or precision position control, stepper motors have limitation due to the cogging torque and no feedback from the position sensor, but it is always better to be considered as a good alternative, because of the advantage mentioned.

5) Linear motor

A linear motor has the stator and rotor unrolled, thus it generates a linear force along its length instead of torque. The most common mode of operation is to use the Lorentz force in which the generated force in proportional to the current and the magnetic field, such as **F**=I**L**X**B,** where **F** is the generated force, I is the current flowing, **L** is the vector of wire whose magnitude is the line length, direction is the current flowing direction, **B** is the magnetic field. Fig. shows U channel synchronous linear motor, where the force is generated from left to right. The linear motor is the straight version of the permanent magnet servo motor as in fig.




U-Channel Linear motor (source:Wikipedia)

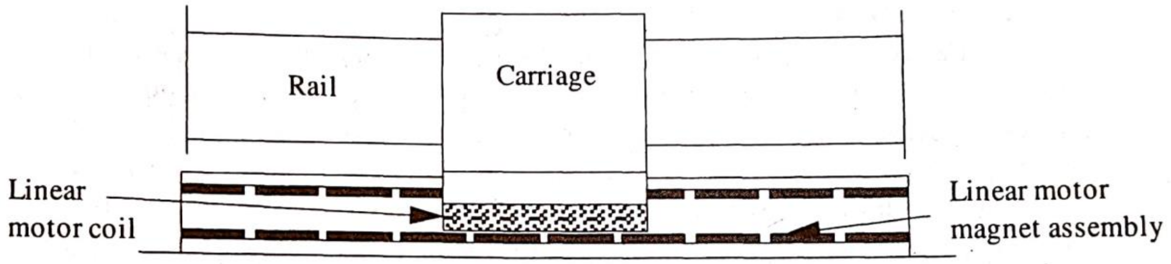


Linear motor as the linear version of permanent magnet servo motor (source:Wikipedia)

## Linear Motor mounting methods

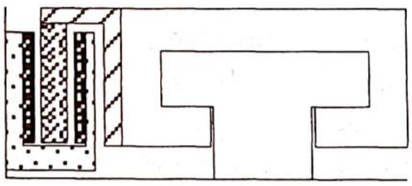
There is very high attractive magnetic force between the coil (usually moving part) and the magnet assembly (usually stationary part) in the linear motor. This attractive force can have a sinusoidal ripple that varies with position, and it can generate the straightness error motion of moving carriage on the slide if the bearings are used to support the linear motor. In order to minimize this effect, the moving coils are usually located between the two rows of magnet (double rail configuration). The forces are then balanced in the double rail configuration, and only small lateral forces are generated due to non-exact centering of the moving coil, or the variations in the magnetic field. The resulting straightness error can be around few micro-inch to few microns, depending on the design and assembly of the machine. The following figures show typical mounting methods for linear motor mounting toward high precision linear motion.

In the first case, the carriage is driven off the centre, so Abbe error can be induced due to the pitching error motion. In the second case, a T shaped bearing is used to minimize the rail deformation, but un-symmetric design can generate the moment, causing the yawing motion error. In the third design, two linear motors are configured symmetrically, thus to reduce any Abbe error. But it has drawbacks in that it needs to solve the synchronous control via master-slave control, for example, and it costs high due to the two linear motors used. The fourth design seems to give ideal linear motor mounting, as one linear motor is located on the centre of the driven mass, but it requires extra grooving in the T carriage with extra manufacturing cost and time.



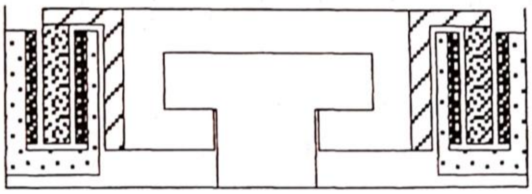

Linear motor mounting located below the moving mass centre

(source: Slocum's precision machine design)



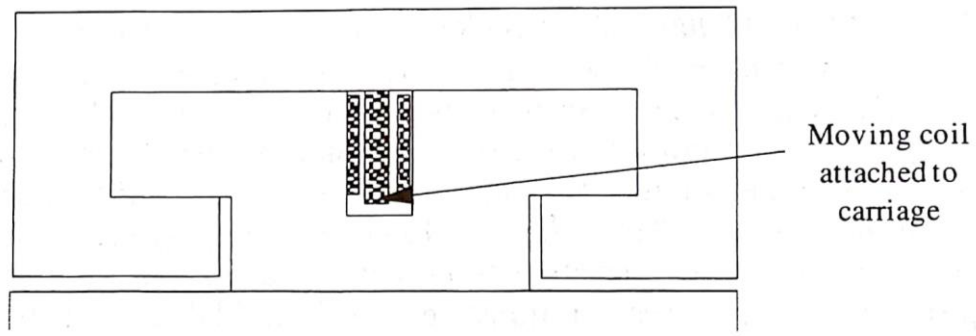
Linear motor mounting located at one side of carriage

(source: Slocum's precision machine design)



Linear motor mounting located at both sides of carriage

(source: Slocum's precision machine design)




Linear motor mounting located on the groove of carriage

(source: Slocum's precision machine design)

Rotary motor or Linear motor

For applications of high torque and high force such as cutting machine tools, the configuration of rotary motor with leadscrew would be ideal for the performance and cost.

For applications of small and medium torque or force such as measuring machines or manipulators, the linear motor can be used due to the simple and compact design with minimum transmission parts. But it should be noted that the main drawbacks of linear motor is the thermal isolation issue. In the linear motor, the generated heat usually conducts to the sensitive part of machine elements such as precision guides and sensors, thus making very high potential for thermal errors in the machine.