# Design Trends

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In this issue of Design Trends:

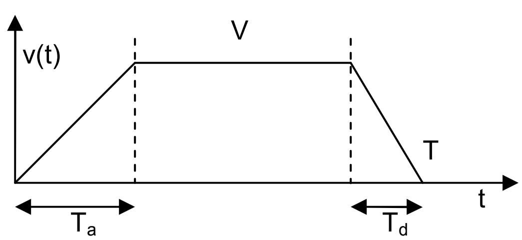


## Motion Profiles

In position control applications there are many ways to move from one point to another. This article reviews some of the most common move profiles and also highlights some of the caveats that may arise. Some simple rules that help with motor sizing are also presented.

### Trapezoidal Moves

Trapezoidal moves derive their name from the shape of the velocity versus time profile.



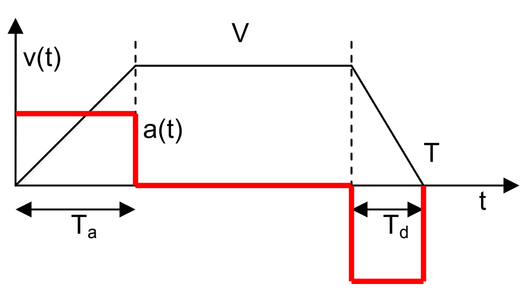

The velocity ramps up linearly to a final velocity V over time $T_a$. Then the velocity ramps down linearly from V to zero over time $T_d$. If the overall move time is T, then the total distance travelled will be

$$D = D_a + D_v + D_d$$

$$D = \frac{V \cdot T_a}{2} + V \cdot (T - T_a - T_d) + \frac{V \cdot T_d}{2}$$

$$D = V \cdot T - V \cdot \frac{T_a + T_d}{2}$$

If only distance D and total time T are specified, there are of course many possible profiles. The acceleration profile is of course discontinuous:



The maximum acceleration and deceleration values are:

$$\max accel = \frac{V}{T_a} = \frac{D}{T_a(T - \frac{T_a}{2} - \frac{T_d}{2})}$$

$$\max decel = \frac{V}{T_d} = \frac{D}{T_d(T - \frac{T_a}{2} - \frac{T_d}{2})}$$

Depending on further move requirements, any of the 3 variables V, $T_a$ and $T_d$ can be further derived from the equations above.

An interesting case is the consideration of power requirements. What move profile would minimize the amount of peak power required? Assuming peak torque is proportional to acceleration, peak power will be proportional to maximum acceleration times maximum speed:

$$P_{\max} \propto V \cdot A = \frac{V^2}{T_a} = \frac{D^2}{T_a(T - \frac{T_a}{2} - \frac{T_d}{2})^2}$$

Since intuitively a symmetrical profile will provide the overall lowest power, we can set $T_d = T_a$ and then optimize for $T_a$:

$$\frac{dP_{\max}}{dT_a} = 0$$

$$\frac{d}{dT_a}\left(\frac{D^2}{T_a(T - T_a)^2}\right) = 0$$

$$(T - T_a)^2 - T_a \cdot 2 \cdot (T - T_a) = 0$$

$$(T - T_a)(T - 3T_a) = 0$$

From this derives the solution $T_a = T/3$, leading to the infamous 1/3, 1/3, 1/3 move profile (1/3 acceleration, 1/3 constant velocity, 1/3 deceleration).
From the above also follows one of the most important power and sizing rules:

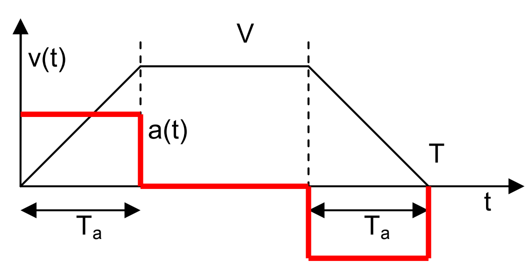
$$P_{\max} \propto \frac{D^2}{T^3}$$

Given a certain distance D and time T for the overall move, maximum power is proportional to distance squared and inversely proportional to time cubed. So if an application was sized for a maximum power of say 100Watts, and one wants to cut the move time in half, then an 800Watt motor will be required (8 times larger!). This can also be used backwards in that if a 200Watt motor was selected for this application, at best one could improve move time by a factor of about 0.8 (i.e. 20% faster).

## More On Power

In addition to the above relationship between peak power and throughput, it is also worthwhile looking at average (or continuous power).

We can re-use the above acceleration graph to calculate average current (here for symmetrical acceleration and deceleration; other profiles have similar results):



Since current (and torque) is typically proportional to acceleration, the RMS (assuming zero current during constant velocity) will be:

$$I_{RMS} = \sqrt{D} \cdot I_p$$

$$D = duty\,cycle = \frac{2T_a}{T}$$

$I_p$ is the peak current during acceleration (and deceleration). The reason for RMS calculation instead of normal average is that motor losses are mostly proportional to $I^2$-R losses, hence the use of a thermal average. The most important conclusion from this formula is the square root of the duty cycle. For example in case of the power optimal profile above, the duty cycle is 2/3 and the RMS current is 0.81 times peak current! So the continuous rating is 80% of the peak rating!

The following is a table of square root values for some duty cycle values.

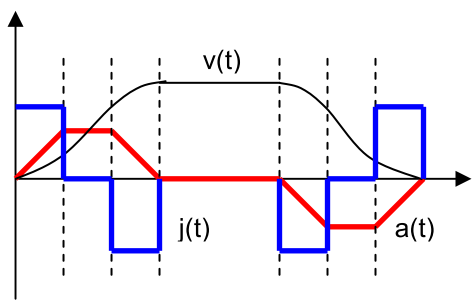
| D | SQRT(D) |
|---|---|
| 0.25 | 0.50 |
| 0.30 | 0.55 |
| 0.35 | 0.60 |
| 0.40 | 0.64 |
| 0.45 | 0.67 |
| 0.50 | 0.71 |
| 0.55 | 0.74 |
| 0.60 | 0.77 |
| 0.65 | 0.81 |
| 0.70 | 0.84 |
| 0.75 | 0.87 |

It is somewhat counter intuitive to see how much larger the RMS values can be in function of duty cycle.

**S-Curve Moves**

The main disadvantage of the trapezoidal move profile is that the acceleration makes abrupt changes. In mechanical engineering this is quantified by "jerk" as the time derivative of acceleration (by the way "snap" is the derivative of "jerk", "crackle" is the derivative of "snap" and "pop" is the derivative of "crackle"…). In the case of trapezoidal moves, jerk is infinite (at least in theory, typically accelerations do not change infinitely fast).

Just as velocity was changed linearly in trapezoidal moves, acceleration is changed linearly in s-curve moves (sometimes also called jerk-free or jerk-limited).




Acceleration a(t) is ramped up linearly to some value $A_{max}$, held constant, and then ramped back down to zero. Jerk j(t) of course goes through some discontinuities.

It is interesting to note that the final velocity V derives from:

$$V = \int a(t)dt = T_a \cdot A_{avg}$$

So from an overall motion profile perspective, one can use the formulae for trapezoidal moves, keeping in mind that the acceleration values are average accelerations.

The maximum acceleration however is:

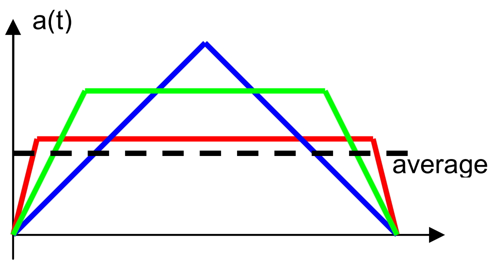
$$A_{avg} = \frac{1}{T_a} \int a(t) dt$$

$$A_{avg} = (1 - \Delta) A_{\max}$$

$$0 \le \Delta = \frac{accel\ ramp\ time}{T_a} \le 0.5$$

$$A_{avg} \le A_{\max} = \frac{A_{avg}}{(1 - \Delta)} \le 2 \cdot A_{avg}$$

So the maximum acceleration is anywhere between the average acceleration (trapezoidal velocity profile) and twice the average acceleration (triangular acceleration profile). The red, green and blue profiles below all have the same average but differing maximum values.




This increase in maximum acceleration is important to note: it increases the peak torque requirement for the motor. Luckily, this peak torque is not required over the whole speed range (in the case of a triangular acceleration profile, it is only required at the half-speed point).

## More Complex Move Profiles

Some applications require more complex move profiles. In the case of complex mechanical systems (like a SCARA robot), the motion path planning may include trigonometric relationships. In the case of oscillatory moves, the position profile may be sinusoidal. In some cases, certain frequencies need to be avoided and the path planning needs to ensure that those frequencies are not triggered.

There are many mathematical methods to create any kind of profile:

- Higher order polynomials with various constraints:
  - End point values and higher derivatives
  - Weight-points (e.g. curve has to go through specific points)
  - Natural splines
  - Curve fitting (LSQ)
- Fourier Transforms
  - Curve is approached with sinusoids
- Wavelet Transforms
  - Curve is approached with wavelets
- Piece-wise curve fitting

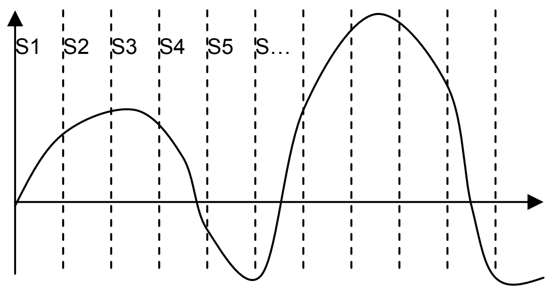
Although all of these methods can ultimately re-produce the original profile with any desired precision, practical implementation and computational friendliness differs greatly. Direct implementation of the profile is also possible, but of course extremely application specific. One of the most generic and computationally friendly approaches is piece-wise cubic interpolation a.k.a. PVT (position-velocity-time).

The concept of PVT is to piece-wise approximate any curve with cubic polynomials. By piece-wise we mean that we do not try to approximate the complete curve with a single cubic polynomial, but rather we split the curve in many pieces and approximate each piece with a cubic.

The general format for a cubic is:

$$x(t) = a_3 t^3 + a_2 t^2 + a_1 t + a_0$$

Graphically then, the piece wise method goes as follows:




The original curve is segmented and each segment will be approximated with a cubic. It is not necessary to have a fixed time period; the segments can be of variable length.

For each segment, we need to determine the 4 coefficients of the cubic. This can be done with following 4 boundary conditions:

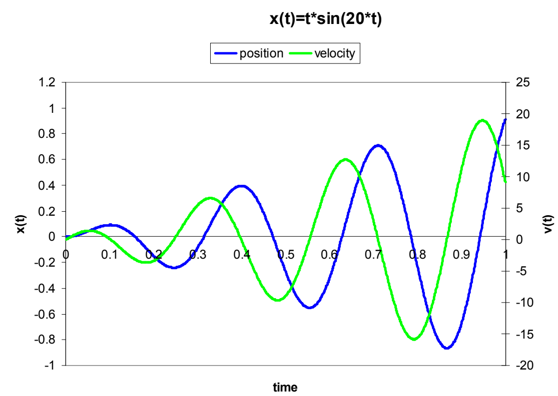
$$x(t_n) = a_3 t_n^3 + a_2 t_n^2 + a_1 t_n + a_0$$
$$x(t_{n+1}) = a_3 t_{n+1}^3 + a_2 t_{n+1}^2 + a_1 t_{n+1} + a_0$$
$$v(t_n) = 3a_3 t_n^2 + 2a_2 t_n + a_1$$
$$v(t_{n+1}) = 3a_3 t_{n+1}^2 + 2a_2 t_{n+1} + a_1 t_{n+1}$$

From these 4 equations, one can derive the coefficients.

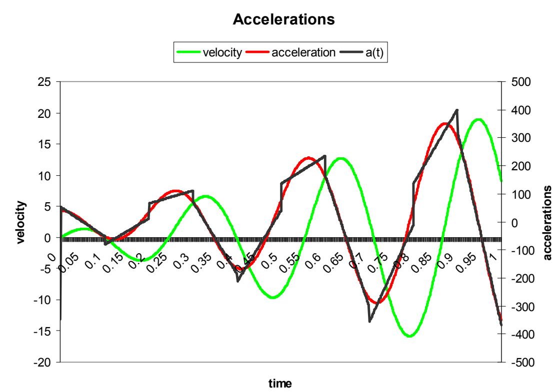
The segment start position and velocity are set equal to the previous segment end position and velocity. This ensures continuity of position and velocity. For each segment, the velocity and acceleration equations are:

$$v(t) = 3a_3 t^2 + 2a_2 t + a_1$$
$$a(t) = 6a_3 t + 2a_2$$

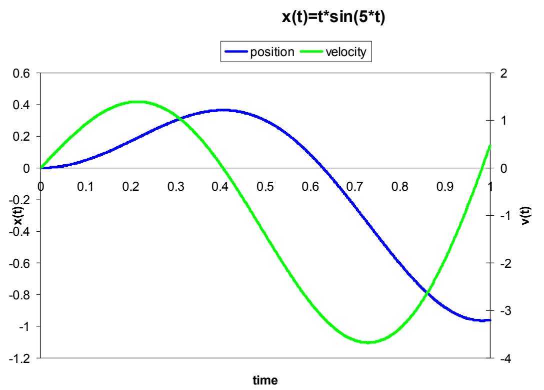
So the accelerations are linear, however not necessary continuous at the segment end points (depends on the original profile).

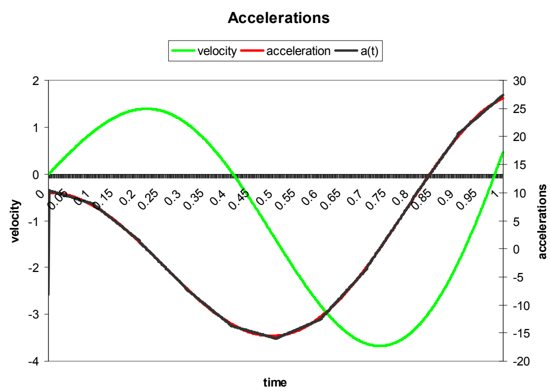



When the above profile is segmented via PVT (at 0.1 sec intervals), the accelerations are as follows:




The red curve is the original acceleration (second derivative of the original position) while the black curve show the piece wise approximation. The acceleration jumps are due to curvature in the acceleration, and the ability to approximate with linear segments. If the curvature is reduced (or alternatively the PVT time period decreased), then the linear approximation of acceleration is much smoother:




This reiterates how PVT allows control over how well any profile can be re-produced. Fundamentally this comes down to signal bandwidth and sampling rate relationships (see Nyquist).

The advantages of PVT are:

- Flexibility (especially the time period)
- Computationally very compact
- Can be used dynamically (on-the-fly) or statically (table)
- Can be used for single or multi-axis moves

## Conclusion

Motion profiles must be determined with some care. As can be seen, the impact on motor power and torque is significant. Although s-curves help smoothen motion, they also change the torque requirements. If the motor power and torque are under-sized, increased following error (or stalling in case of stepper motors) will result from torque saturation. PVT can help build motion profiles that optimize throughput and available power.

## Stegmann Hiperface DSL

HIPERFACE DSL® is a purely digital protocol needing a minimum of connections between drive and motor-feedback system. The robustness of the protocol allows the connection to the motor-feedback system signals within the motor cable. Motor-feedback systems with the HIPERFACE DSL® interface can be used for all performance ranges and simplify the implementation of an encoder system within a drive significantly.

Some of the main advantages of HIPERFACE DSL® result from the possibilities to connecting the encoder:

- One digital interface on the drive for the complete communication to the motor-feedback system. The interface conforms to the RS485 standard with a transmission rate of 9.216 MBaud.
- Communication to the encoder on a single line pair
- Encoder power supply and communication can be placed on the same line pair. This is enabled by adding one pulse transformer component to the drive (power + signal).
- Connection lines to the encoder can be placed as a shielded twisted pair line within the motor supply cable. This eliminates the encoder connector on both motor and drive.
- Cable length between drive and motor-feedback system can be up to 100 m without derating of performance.

The digital protocol HIPERFACE DSL® can be used in a variety of drive applications:

- Cyclical data transmission synchronized to the feedback cycle of the drive. This allows synchronous processing of encoder position and speed.
- Cycle times down to 12…15 µs can be supported.
- Transmission of absolute position of the motor-feedback system with a maximum cycle time of 195 µs.
- Redundant transmission of absolute position with a maximum cycle time of 195 µs for the use of suitable motor-feedback systems in SIL2 applications (according to IEC 61508).
- Transmission of second channel absolute position with a maximum cycle time of 195 µs for the use of suitable motor-feedback systems in SIL3 applications (according to IEC 61508).
- Parameter channel for bidirectional general data communication with a bandwidth of up to 340 kBaud. This data includes an electronic type label for identification of the motor-feedback system and for storage of drive-related data in the motor-feedback system.
- Pipeline channel for transmission of data from external sensors related to the motor that are linked to the motor-feedback system via the Hiperface DSL® SensorHub protocol.

# Product Feature: Arcus DMX-DRV Controller Mode

## Introduction

Stepper motor drives typically accept pulse and directions signals from a higher level controller (a.k.a. indexer). The 2 most common interfaces are pulse and direction and CW/CCW signals.

Some applications however only consist of simple back and forward motion to be triggered by I/O (for example from a PLC or even simple push buttons). In those applications the addition of an indexer can be cost prohibitive or add unnecessary complexity.

Arcus Technology has added a simple I/O triggered controller mode to the DMX-DRV series of integrated stepper motors and drives.

## The DMX-DRV Series

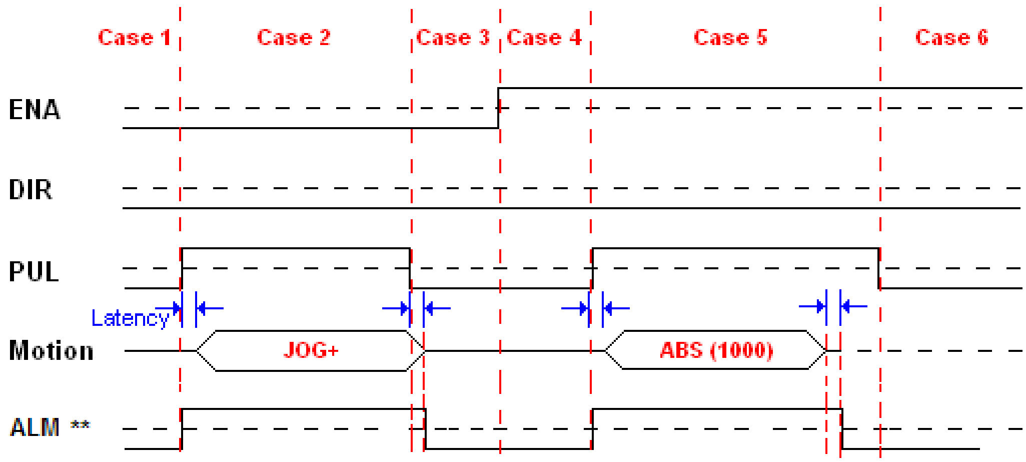
The DMX K-DRV is an integrated step motor, driver, and controller with the following features:

- 12-24VDC voltage input
- 100mA to 2.5A peak current setting
- Full/Half/Quarter/16 microstep
- One clock (Pulse/Dir) or Two clock (CW/CCW) support
- 200K maximum pulse rate support
- 16K maximum pulse rate (controller mode)
- 4 selectable motion profiles (controller mode)
- Opto-isolated differential Pulse/Dir (CW/CCW) inputs
- Opto-isolated driver enable input
- Opto-isolated over-temperature alarm output
- In position output (controller mode)
- Integrated controller using DIO control
- Available in NEMA 11, 17, and 23 motors in various stack sizes

## Controller Mode

The DMX-K-DRV can be configured as a basic controller. When configured in controller mode, the Direction, Enable, Pulse and Alarm signals are used for DIO Control:

- Direction, Enable: Used to select one of the four motion profiles
- Pulse: Used to trigger a motion profile or to abort a current move
- Alarm: Used as an in-position output if the “Over Temp Shutdown” feature is disabled



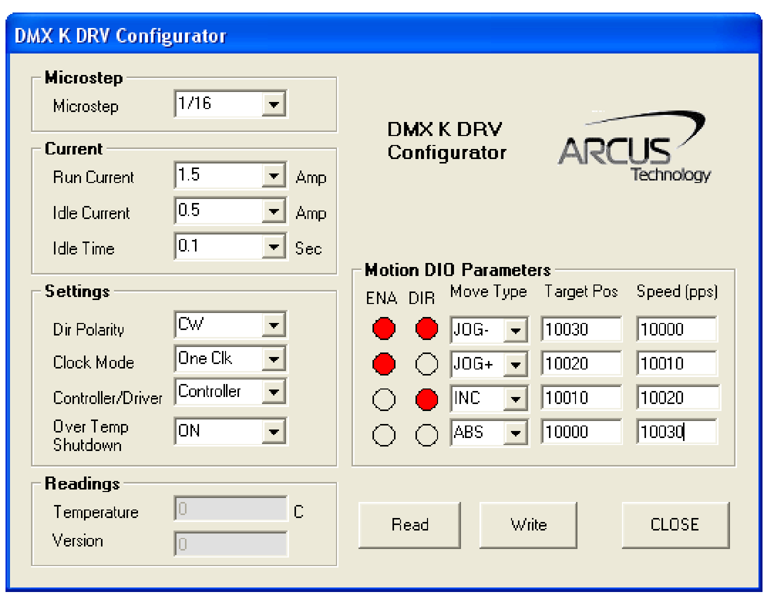

* Latency = 500-550 us

** If Over Temp Shutdown is disabled, the alarm output is used as an "In Position" output. The signal will turn on while the motor is in motion, and turn off when the motor is idle.

**Case 1:** ENA=0, DIR=0, PUL=0 – DMX-K-DRV is idle. Chosen motion profile is JOG+.
**Case 2:** ENA=0, DIR=0, PUL=1 – DMX-K-DRV is jogging in the positive direction at a speed of 10000 pps. Motion starts on the rising edge of the PUL signal.
**Case 3:** ENA=0, DIR=0, PUL=0 – DMX-K-DRV has stopped all motion on the falling edge of the PUL signal.
**Case 4:** ENA=1, DIR=0, PUL=0 – DMX-K-DRV is idle. Chosen motion profile is ABS with a target position of 1000.
**Case 5:** ENA=1, DIR=0, PUL=1 – DMX-K-DRV is moving to pulse position 1000. Note that the motor will stop once the desired position is reached, regardless of the PUL signal.
**Case 6:** ENA=1, DIR=0, PUL=0 – DMX-K-DRV is idle.

## Configuration

Configuration of the controller mode is done via Arcus' easy to use setup software.



## Application Solution:  Linear Servo Motor Systems

Linear servo motors were somewhat of a novelty act 15 years ago. Availability of linear servo motors was very limited, costs were relatively high, and implementation was not for the faint of heart and somewhat experimental.

Today, linear servo motors have become much more main stream. There are a substantial number of motor manufacturers, various motor types, prices have come down significantly and much more application knowledge is available.

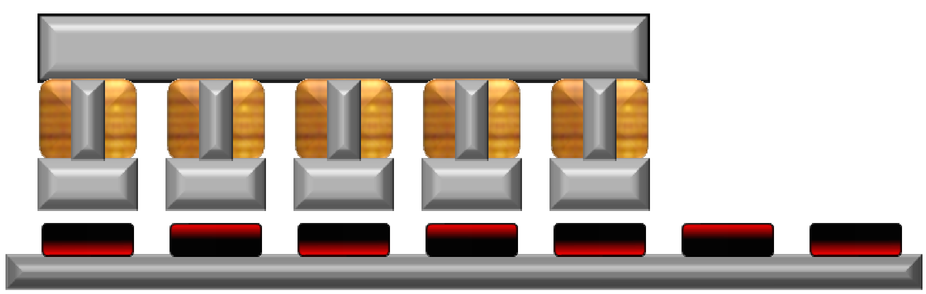
### Linear Servo Motor Operation

Fundamentally linear servo motors operate just like rotary brushless servo motors. Instead of generating torque, they generate force of course via the interaction of permanent magnets and 3-phase currents. Just like there are various types of rotary motor designs, there are a few different linear motor designs as well, the main 3 being:

- Iron core
- U-channel
- Tubular

In theory the linear voice coil is also a linear brushless servo (with very limited travel range), but we focus here on 3-phase type motors.

The iron core motor consists roughly of a single row of permanent magnets and a 3-phase coil that is kept at a close distance to the PM (the “air gap”).

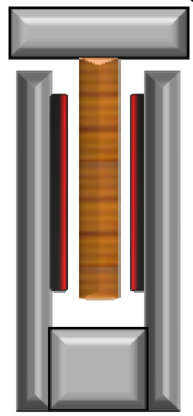


Although this design tends to have a lower parts cost due to the limited number of magnets and also is relatively modular (as smaller magnet plates can be lined up to create a longer motor), the trade-offs are not insignificant:

- Very large attractive force between coil set (forcer) and the magnets (300N and higher depending on motor size). This of course requires a significant bearing system.

- Requires a very tightly controlled air gap between the coil and the magnets. This makes it difficult to assemble and integrate.
- Cogging and heat losses due to the iron core.
- Overall lower efficiency due to core losses and friction losses resulting from the attractive forces. Overall magnetic circuit also has significant losses due to fringing.
- The magnet track is fully exposed and attracts metal particles, resulting in possible clogging.

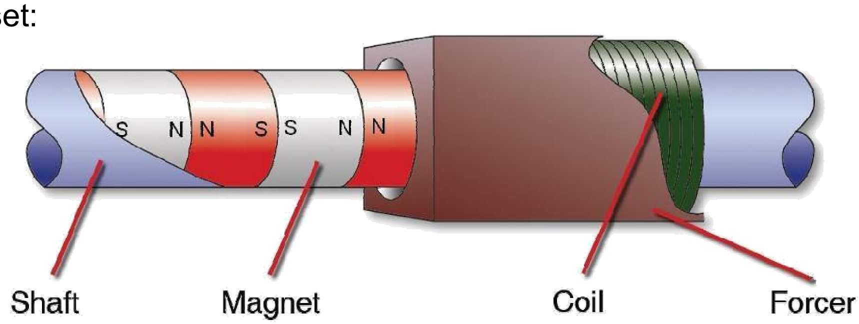
The U-Channel motor consists of a dual row of magnets with a 3-phase coil in between:



Because of the additional magnets, the cost of this motor type is higher. These motors are either executed with or without back iron in the coil. In the case of ironless designs cogging and iron losses are mostly eliminated. Due to the lateral symmetry, there is no longer an attractive force for the ironless type. The iron core type does have a downward attractive force. Trade-offs for this type are:

- Sub-optimal magnetic design due to magnetic field fringing
- High thermal resistance for the heat generated in the coil leads to de-rating
- Tends to pitch as the distance between the point of attachment to the load and the point where the force is generated is large. This also reduces the stiffness.
- Relatively large cross section
- Requires tight air gap control

The tubular style motor consists of a cylindrical shaft with magnets and a 3-phase ironless coil set:



The magnets are mounted inside the shaft without any spacers, with like poles facing each other. This increases the overall magnetic flux significantly. The 3-phase coils completely wrap this high magnetic flux, completely optimizing the magnetic circuit design. The large flux density allows a larger air gap between the shaft and the coils. There is no attractive force between the forcer and the magnets. The eccentricity of the shaft relative to the coil does not affect force, making this the most forgiving linear motor design on the market. Since the coil has 4 heat sinking surfaces and there is no back iron, thermal losses and heat generation are minimal and thermal resistance is minimized. The distance between mounting surface and force generation point is minimal which improves stiffness and avoids pitching.

## Linear Motor Target Applications

Traditionally linear servo motors were limited to applications that require both very high speed (meters per second) AND high precision (sub micron). Belt driven systems are typically suitable for high speed, but not high precision whereas ball screw driven systems are good for high precision but not high speed (critical speed limitation).

With the availability of the various linear servo motors, this delineation is no longer as clear. When considering the overall system cost (parts cost, engineering cost, assembly cost, maintenance cost…) linear servo systems are becoming much more attractive. They are no longer restricted to just high speed and high precision. More and more high speed systems (i.e. 1meter/s and up) use linear servo motors. Belt driven systems often require gear boxes for inertia matching, so when comparing side-by-side the overall cost of a gear box driven belt system and a linear servo system, the cost differences are no longer significant. Same holds for precision systems. These often require precision ground ball screws with pre-tensioning and load mounted linear encoders. Assembling such a system can be very time consuming and requires tight tolerance control.

Some of the applications where linear servo motors have been used and are now being used include:

- Metrology (X-Y-Z precision positioning)
- Wafer Inspection (precision positioning)
- Lab automation (high speed transfer axes)
- Sand blasting (high speed reciprocating)
- Optical systems (lens adjustments)
- Wire bonding (high speed and precision)
- …

## Application Considerations

When considering a linear servo motor for an application, there are some important considerations (but also some important restrictions that are removed!):

- **Sizing**

Just like a rotary motor, a linear motor needs to be sized based on peak and continuous force, as well as speed. Similar current and voltage considerations apply as with rotary systems. Compared to lead screw driven systems, there is one significant difference, which is force stiffness. A ball screw acts as a rotary-to-linear converter and torque is translated into force per the screw pitch. The resulting “stiffness” can be quite large (also due to inefficiencies in the lead screw mechanism). Linear servos typically do not provide that kind of stiffness (unless you over size dramatically). Sizing is mostly based on acceleration and mass for peak force and duty cycle for continuous force.

- **Orientation**

Linear servo motors will drop when power is removed in case of vertical applications. The option of a rotary brake on the back of the motor no longer exists. A separate braking mechanism needs to be added directly.

- **Brushless Motor Commutation**

Just like rotary motors, commutation can be performed with encoder and Hall signals, or any other absolute feedback device. When using incremental encoder only, start-up routines will create some direct linear motion, which depending on the motor pole pitch may be significant. More advanced encoder-only startup routines can be used in those cases.

- **Inertia Matching**

Inertia matching is no longer a consideration! Most systems are mechanically stiff enough that the ratio between the load and motor mass is simply not a factor. What is important however is stiffness between force generation and position feedback (Abbe Error). See discussion above about different motor types’ stiffness.

- **Servo Tuning**

Because a linear servo system is a direct drive system, servo loop tuning differs quite a bit from traditional rotary motor tuning. Because the friction is typically very low, some damping needs to be created in the servo loop. Derivative gains are hence very important. To improve the performance of a derivative gain (i.e. numerical differentiator), some attention needs to be paid to update rates and feedback resolution. It is recommended that feedback resolution is not just chosen based on positioning resolution, but is also selected based on the need for a good derivative.

For more information about any of the above topics or general questions or comments, please contact us: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- www.arcus-technology.com: Arcus Technology manufactures stepper motor, drive and controller technology, providing USB, Ethernet and Mod-Bus connectivity.
- www.nipponpulse.com: Nippon Pulse manufactures the unique linear shaft motor, a direct drive linear brushless servo motor.
- www.stegmann.com : Stegmann is a leader in high performance motor feedback solutions.
- www.technosoftmotion.com : TSM is a leading DSP motion control technology company specialized in the development, design and manufacture of digital motor drive products and custom motion systems.

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