Design Trends

A quarterly publication brought to you by Motion Designs Inc. February 2011

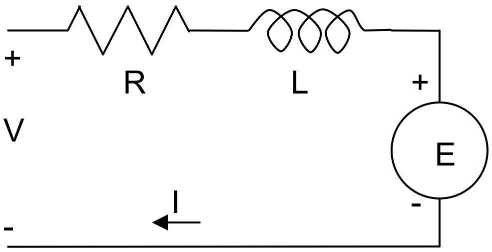
In this issue of Design Trends:

Motor Voltages

Regardless of the motor type (stepper, brushless, brush DC, linear…) in order to operate the motor at its maximum power level (torque and speed), sufficient voltage must be available. Bus voltage calculations are very often over looked when sizing motors and drives, and it is not until much later that voltage limits the application. In what follows we take a closer look at overall voltage requirements with regards to speed and torque objectives.

Electric Motor Operation

Any electric motor has an equivalent electric circuit that can be used to calculate required voltages (for multi-phase motors this circuit would be a single phase representation):



The resistance R is due to the copper wire used to create the windings, the inductance L is due to the magnetic circuit formed by the primary and secondary circuit. The voltage E (the back EMF voltage) is due to the induced voltage from the secondary circuit. In the case of stepper motors and brushless permanent magnet motors the back EMF (Electro Motive Force) is due to the magnets on the rotor. In the case of brushed DC motors it is due to the permanent magnets on the stator or the field winding. From a power perspective, the motor converts electric energy to

mechanical energy. The electric energy going into the motor is:

$$v(t) = R \cdot i(t) + L\frac{di(i)}{dt} + e(t)$$

$$p(t) = v(t) \cdot i(t)$$

$$= R \cdot i(t)^2 + L \cdot i(t) \cdot \frac{di(t)}{dt} + e(t) \cdot i(t)$$

$$p(t) = Ri(t)^2 + \frac{1}{2}L\frac{di(t)^2}{dt} + e(t) \cdot i(t)$$

The first component is the resistive loss resulting in heat. The second component represents magnetic circuit energy which has a zero steady state value. The last component is the power that is converted to mechanical energy.

The mechanical energy is of course torque and speed dependent as follows:

$$p(t) = \omega(t) \cdot T(t) = e(t) \cdot i(t)$$

There are some additional losses associated with the electric to magnetic to mechanical power conversion (hysteresis, bearing friction, Eddy losses…) but they are relatively small.

The motor back EMF is proportional to motor speed hence:

$$\omega(t) \cdot T(t) = K_e \cdot \omega(t) \cdot i(t)$$

$$T(t) = K_e \cdot i(t)$$

The above equation is only true if there is a certain phase relationship between all the variables (which is established by the commutator in DC motors, by dynamic commutation in brushless motors, but is variable in open loop steppers in which case this is a specific operational condition namely at the pull out point).

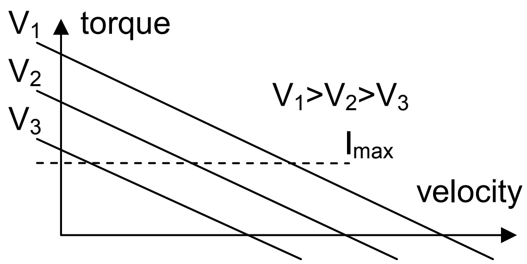
So the back EMF (or voltage constant) also represents the torque constant (i.e. how much torque is produced by the current).

Torque-Speed and Voltage Relationship

Based on the above equations then, a first approximation can be made for the torque and speed relationship. In steady-state:

$$V = R \cdot I + E = R \cdot \frac{T}{K_t} + K_e \cdot \Omega$$

If the motor voltage is held fixed, then this establishes an operational line:



The maximum speed (at zero torque) is V/K_e. The maximum torque (at zero speed) is $V*R/K_t$. The current associated with this maximum torque may be too high (for example it may demagnetize the motor), so often there will be an upper limit as shown by the dashed lines.

The most important conclusion however is that the maximum available bus voltage will impose a limitation on the maximum speed, the maximum torque, but most importantly on the achievable operating point.

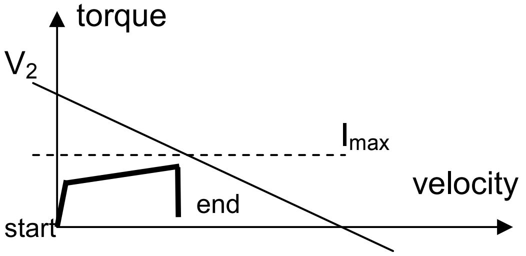
Operating Points

In a typical motion control application, a load must be ramped up to speed. The torque required to reach a certain speed will be composed of:

- Acceleration torque
- Friction torque
- Gravitational torque (if non-horizontal)
- External load torque

The acceleration torque is proportional to the overall system inertia and the acceleration (which is speed over acceleration time). Friction torque is typically proportional to speed.

The combination of the speed to reach and the overall torque required establishes a point in the torque-velocity plane that needs to fall below the operational line.



The thick line represents the path in the torque-velocity plane to ramp up from zero speed to some speed. There is an initial large jump during the initial acceleration, a gradual increase in friction, and then once the final speed is reached, the acceleration torque drops off and just the frictional torque remains.

The key point here is that the worst case point (right at the end of acceleration but also at almost maximum speed) must fall within the operational area of the motor and its maximum bus voltage. It is not sufficient that the end point is within the operational area.

If the desired path goes outside the operating area, then the desired speed will not be reached in the expected amount of time.

From the equations above, one can also consider the operating point with maximum power:

$$V = R \cdot \frac{T}{K_t} + K_e \cdot \Omega$$

$$P = T \cdot \Omega = \frac{K_t}{R}(V \cdot \Omega - K_e \cdot \Omega^2)$$

By taking the first derivative, one can see that power is maximal at:

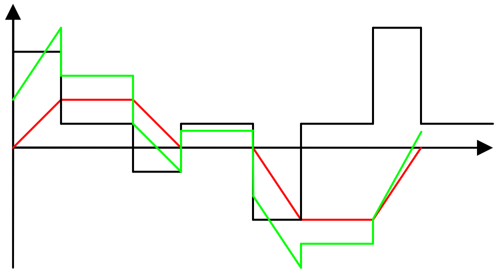
$$\frac{dP}{d\Omega} = \frac{K_t}{R}(V - 2 \cdot K_e \cdot \Omega) = 0$$

$$\Omega = \frac{V}{2K_e}$$

So this is at the mid-way point of the maximum speed.

Sizing

The most accurate way to determine the maximum motor voltage is by plotting both the velocity and current waveforms. Knowing that the back EMF and torque are proportional to both curves respectively helps in visualizing worst case conditions.



The case above is a load that is moved up first and then down. The current requirement is both for acceleration and gravitational force. The black line is the current profile and the red line is the

speed. The green line is the sum of the current times resistance plus velocity times voltage constant. This helps pin point the worst case voltage and torque point (when maximum speed going downwards is reached in this case).

It is recommended to leave at least 20% head room between worst case motor voltage and DC bus voltage.

Sensitivity

The resistance and voltage constant values can also be considered as margin parameters as follows.

For every extra Ampere (which is derived from torque/K_t) there is an additional voltage drop of R volts. So if a motor has a high resistance, then any unforeseen increase in current (due to torque) will cause a high drop in voltage margin (potentially making it negative i.e. reduction in speed).

For every extra motor rpm there will be a required extra voltage of K_e (V/rpm). If the motor has a high voltage constant then higher speed may not be possible.

Practical Considerations

Motor K_e and K_t values are often published in various units. In theory, for a DC brushed motor, when both are specified in SI units they are numerically equal. In SI units, K_t is in units of Nm/A and K_e is in units of V/rad/s. Other units often used are:

- K_t: Nm/Arms, oz-in/A, lbs-in/A…
- K_e: V/Krpm, Vrms/rpm…

For brushless motors, due to the multi-phase nature of the motor, a simple 1:1 correspondence does not exist. Only on a per-phase do the K_e and K_t equal each other. For the overall 3-phase system, the following derivation is required. Assume that each phase has a $K_{t,p}$ torque constant (per phase). The overall torque for phase currents with amplitude A and proper phase angle (i.e. commutation) is:

$$T = K_{t,p}(A\sin^2\theta + A\sin^2(\theta + \frac{2\pi}{3}) + A\sin^2(\theta - \frac{2\pi}{3}))$$

$$T = K_{t,p} \cdot A \cdot \frac{3}{2}$$

If the phase-to-phase back-EMF is K_e, then the phase-to-neutral $K_{e,p}$ is K_e/sqrt(3). So the relationship between the overall torque constant (based on all phase currents) is:

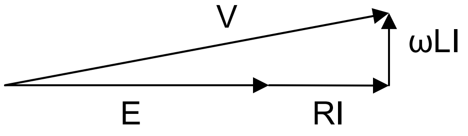
$$T = K_e \frac{1}{\sqrt{3}} \frac{3}{2} A = 0.87 \cdot K_e \cdot A$$

$$K_t = \frac{T}{A} = 0.87 \cdot K_e$$

In the case of brushless motors, because the motor currents are sinusoidal, it may be required to include the inductive voltage component. The voltage across an inductor is:

$$V = j \cdot \omega \cdot L \cdot I$$

In addition, this voltage needs to be included as a vector:

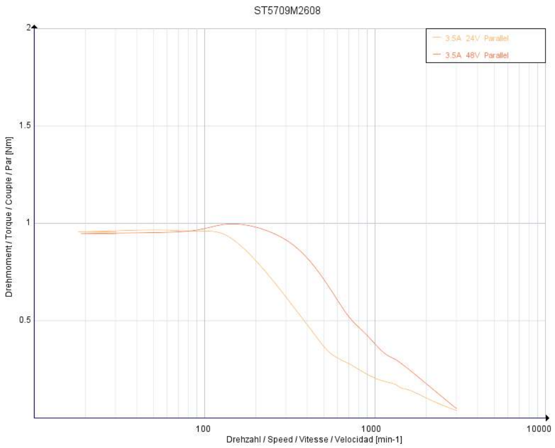


In many cases, this voltage is small, and due to the vector nature does not affect the motor voltage much. For example a 4-pole motor at 3,000 rpm and 1mH inductance has an ωL=0.628.

But for example a 10-pole motor at 6,000 rpm with 5mH inductance has ωL=15.7

All motor parameters (K_e, K_t, R, L) vary with temperature and also from unit to unit. K_e and K_t values are typically specified with a +/-10% tolerance. Resistance can go up by a factor of 2 as the motor heats up. Inductance can go up by a factor of 3 as a function of temperature and current (due to magnetic saturation)

Stepper motors are even more complex to analyze, but they benefit from the fact that torque speed curves are generally available for each motor.



Conclusion

Motor voltages should be included in any motor sizing. Otherwise DC bus voltage limitations will affect the performance of the overall system. This can be exhibited by the inability to reach higher speeds or oscillations in the system due to the non-linearity introduced by voltage saturation.

NPM Linear Servos

Nippon Pulse has introduced the L160 Linear Shaft Motor, a tubular style linear servomotor. The L160 is the fourth release in Nippon Pulse's low maintenance L-series line, joining the L250, L320, and L427. The L-series motor features a larger non-critical air gap (up to 65%) than available on the standard S-series models.

The L160 features a non-critical air gap of 0.8mm, 0.3mm greater than on the standard S160 Linear Shaft Motor. In addition, the L160 has a Continuous Force of 8.8~18N, an Acceleration Force of 35~70N, an Acceleration Current of 2.2A, and a stroke length between 100 and 1,800mm.

The L-series motors reduce machining costs, allow for greater variance when machining a stage, extend time needed between routine cleanings, and are ideal in high debris environments. Because the air gap between the forcer and shaft is non-critical, any debris build-up on the shaft does not reduce generated force.

Within the L-Series motors, the L250 size now also has shorter forcer versions. The L250SS, L250DS and L250TS are short forcer versions with forcer length of 50, 80 and 80 mm respectively.

The Linear Shaft Motor is also used in the SCR and SLP stages from Nippon Pulse.

The Linear Shaft Motor is the first linear motor designed for the ultra high-precision market. The design maximizes use of magnetic flux, provides stiffness 100 times greater than similar motors, and minimizes heat production. As a result, the Linear Shaft Motor can achieve sub-micron resolution movements.

Product Feature: AMO feedback robustness

Introduction

Linear and rotary feedback devices typically use optical or magnetic principles to measure position. Both technologies have some significant advantages and disadvantages:

Optical Feedback

Advantages:
- Very high resolution capability
- Very high speed capability
- Very high accuracy and repeatability
- Immune to external magnetic fields
- Cost effective for lower performance implementations (low resolution, non-glass)

Disadvantages:
- Very sensitive to humidity and contamination
- Very sensitive to temperature
- Difficult to install, align
- Expensive for higher performance implementations

Magnetic Feedback

Advantages:
- Very high speed capability
- Not sensitive to humidity
- Easier to install, align
- Cost effective

Disadvantages:
- Only has lower resolution capability
- Low accuracy and repeatability (hysteresis)
- Very sensitive to external magnetic fields
- Sensitive to temperature

AMO Inductive based feedback

Unlike any optical or magnetic encoder, AMO inductive feedback is developed based on AMOSIN ® Inductive technology, where high-precision is achieved by scanning stainless steel photo-lithographically etched structures with sophisticated inductive sensors and processing the signals with proprietary integrated electronics (ASIC).

The AMOSIN ® length measuring systems can be supplied as open non-contact encoder or as a non-contact guided linear guide way rail as an alternative to encapsulated (extrusion) optical encoders.

The angle measurement systems are ring scales with open hollow large bore thru holes and have non-contact inductive scanning of the graduation pattern ring with no coupling or mechanical connection, for easier application to rotary feedback applications.. The AMOSIN ® systems offer high resolutions up to 0,125 microns on the circumference and accuracies to ± 3 µm / m, with an IP 67 rating that is extremely resistant to environmental influences such as dust, moisture and have an extremely high shock and vibration resistance.

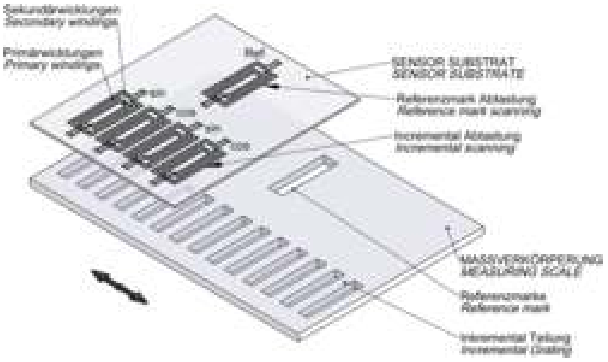
The high accuracy inductive angular encoders are comparable to the optical measurement systems in accuracy and resolution, due in part to the manufacturing process of the rigid stainless steel scale tape measure that provides an excellent sensor signal output with sine wave accuracy deviations of <0.1% (harmonic content as a measure of the achievable interpolation within a period of pitch). The measuring principle is described below. The measuring system does not include any magnetic parts and is, in contrast to magnetic measurement systems, totally resistant to any kind of electromagnetic interference and has no hysteresis.

Following the principle of the data acquisition of the position measurement systems are divided into the following categories:

- Incremental measuring systems
- Absolute measuring systems

Operation

The AMOSIN ® systems operate on the principle of a transformer with a moving reluctance. The mutual inductance of the primary and secondary windings of a transformer changes depending on the relative position with respect to the core. The AMOSIN ® system consists of a planar micro-coil structure and a measurement scale. The coil structure with a plurality of coils aligned in the direction of measurement (individual sets of micro-coils for Sine and Cosine), is incorporated on a substrate with micro-multi-layer flex circuit technology. The scale is a stainless steel scale with a high-precision photolithographic etched periodic graduation (eg λ = 1000 microns) with variable reluctance.

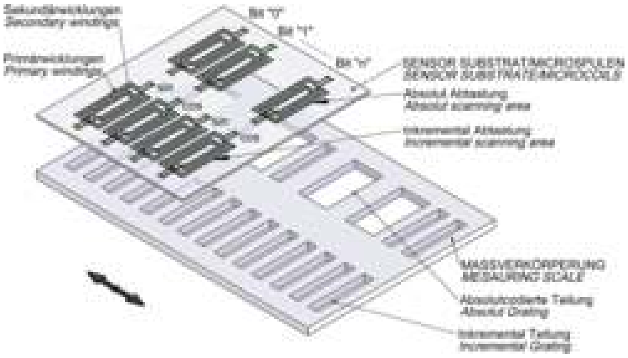


The relative motion in the direction of measurement between the inductive sensor (encoder head) and measuring scale periodically changes the mutual inductance of each coil and generates two sinusoidal 90 ° phase-shifted signals (SIN and COS). With the excitation pure Sine wave signal, the resultant output is an excellent signal quality and stability against environmental influences so that after the signal conditioning in the evaluation electronics, the error is only 0.1% deviation from the ideal sinusoidal shape (harmonic content). This allows high interpolation (subdivision levels) in the digital signal, either in the measurement system or in the subsequent electronics (CNC, etc.).

A key feature of the functional principle is that the AMOSIN ® inductive scanning does not result in electrical hysteresis. Due to the high-frequency alternating field, along with low pass filtering, and in contrast to magnetic systems, the material hysteresis is completely suppressed. The signal processing evaluation electronics of the inductive sensor output is interpolated continuously and in real time without strobe times and the output of the differential line drivers can be either 1 Vpp sine wave or square wave.

In addition to the periodic quadrature output signals (A, B and their inverted), a reference index pulse signal is available for the determination of absolute orientation. This reference index signal is generated with an index mark on the measurement scale and does not need an any external additional switching elements

ABSYS absolute measurement system



For the ABSYS absolute measurement system, an additional coded pattern is used in parallel to the periodic grating pitch with code-sharing. This encoding is detected by the scanning head inductively. The read binary word is unique for the full scale length and thereafter is a "look up table" to convert the data into an absolute linear or angular value. For high-resolution positioning, the evaluation of the incremental graduation, as described above, is merged with the absolute position.
Up to about 30 000 mm in length, or diameter up to 10 000 mm, with resolutions in the submicron range, are possible.
The position data are transmitted via serial interfaces (SSI, BISS, etc). In addition sine wave 1 Vpp signals can be supplied.

The wide range of applications of AMOSIN ®-length and angle measuring systems covers a wide range of applications from extremely precise positioning in quality control machines, assembly machines, metalworking machine tools, to direct driven linear motor axes where high dynamic stiffness is required.

General Properties

- Insensitive to coolant, oil or dirt - IP67
- Insensitive to magnetic fields
- High accuracy
- High resolution
- Easy installation, integrated auto-calibration
- Speeds up to 30 m/s, and 70 000 rpm

Applications

- Machine tools
- Direct drives
- Sheet Metal Working Machines
- Insertion machines
- Measuring machines

Application Solution: High Speed Belt Drive

Timing belts and pulleys have been around for decades and are the work horse of mechanical transmissions in many applications and industries. Although they originated in the automotive industry for engine valve control (hence the name timing belt), their use is universal.

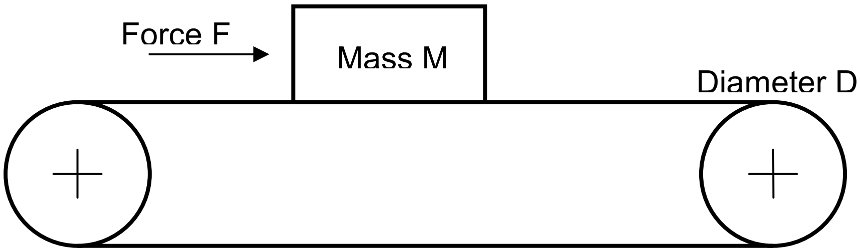
In motion control applications, timing belts are typically used as:

- Rotary-to-rotary reduction mechanisms
- Rotary-to-linear motion conversion

It is as a rotary-to-linear converter that they are particularly cost effective.

Linear Belt Drive Equations

Assuming the standard configuration as follows:



Since one of the pulleys is powered by a motor, we need to reflect all the linear physical entities to the rotary pulley shaft.

The mass M (in kg) has a reflected rotary inertia of (we use subscript l for load)

$$J_l = M \cdot (\frac{D}{2})^2$$

An external force F (in N) (gravity, acceleration, …) will result in a torque T (Nm)

$$T = F \cdot \frac{D}{2}$$

The linear distance traveled per pulley revolution is of course the circumference

$$C = \pi \cdot D$$

Torque, speed and inertia

Because of the “magnification” between rotation and linear travel, for typical applications the resulting torque and motor speed are not near the optimal motor operating point. For example, a vertical application with a 15kg mass and 50mm diameter pulley results in a motor torque of 3.68Nm, but for a 0.5 m/s speed this would only require 190 rpm motor speed. As discussed above, optimal motor power is achieved at higher speeds.

In addition, the reflected load inertia would be 94 kg.cm2, which is relatively high and would result in a high inertia ratio for typical sized motors.

Gear Reduction

By adding a gear reducer R between the motor and pulley, the above formulas become:

$$J_l = \frac{M}{R^2} \cdot (\frac{D}{2})^2$$

$$T = \frac{F}{R} \cdot \frac{D}{2}$$

As a result, the motor can be operated at higher, more optimal speeds. The inertia ratio between reflected inertia and motor inertia can be significantly reduced. The torque requirements for the motor are reduced.

Because adding a gear reducer to an existing pulley arrangement can be difficult, Onvio has created an integrated pulley+gear reducer called a “power pulley”.

The PL series comes in 4 different sizes, PL-005, -010, -020 and -030. Not only does this approach reduce the overall size, it also lowers the cost by eliminating a complete pulley shaft and bearing arrangement.

The belt contact area of the pulley is centered over the gearbox output bearings providing higher capacity and more rigidity for high speed, high dynamic belt applications.

The following table provides an overview of the PL series ratings:

Model	PL-005	PL-010	PL-020	PL-030
Ratios	3, 5, 7, 10	3, 5, 7, 10	3, 4, 5, 7, 10	3, 5, 7, 10
Rated Output Torque	Up to 6Nm	Up to 22Nm	Up to 40Nm	Up to 100Nm
Max. Input Speed	8,000 rpm	6,000 rpm	6,000 rpm	4,800 rpm
Size	57x57x75 mm	70x70x96.2 mm	90x90x116.3 mm	120x120x150.2 mm
Backlash	≤12 arc-min			
Efficiency	>97%			
Weight	0.70 kg	1.60 kg	3.3 kg	7.3 kg

For right angle mounting, a 1:1 right angle stage can be integrated, resulting in the FL Series:

For more information about any of the above topics or general questions or comments, please contact us:

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Motion Designs is a technical sales and engineering company with extensive machine and motion control experience. We work with some of the best manufacturers in the industry as witnessed by our present line card:

- www.amosin.com: AMO manufactures induction based precision linear and angle measurement encoders.
- www.arcus-technology.com: Arcus Technology manufactures stepper motor, drive and controller technology, providing USB, Ethernet and Mod-Bus connectivity.
- www.nanotec.com: Nanotec provides a comprehensive range of stepper and servo motor solutions.
- www.nipponpulse.com: Nippon Pulse manufactures the unique linear shaft motor, a direct drive linear brushless servo motor.
- www.onviollc.com : Onvio is a premier US manufacturer of planetary gearboxes, cycloidal gear reducers and highly engineered timing pulleys.
- 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.