Load Inertia and Motor Selection

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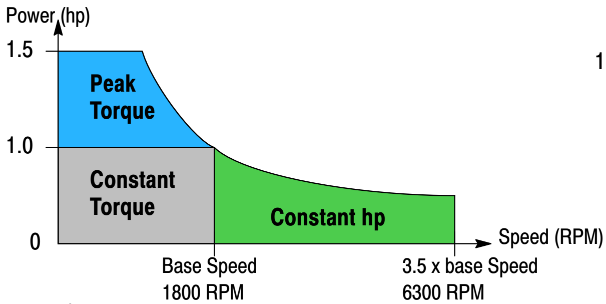
Consider matching load and motor inertia. Mismatch can extend the time to speed (acceleration time), and excessive mismatches produce less than optimal response and can waste power.

Induction motors

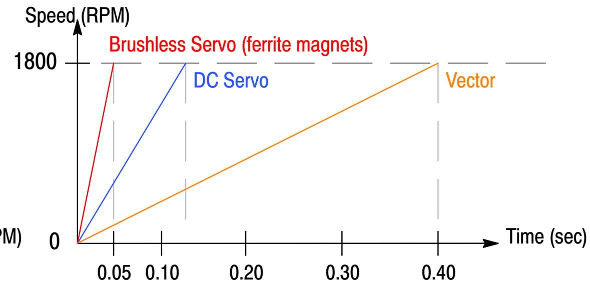
Because a motor's speed can be varied does not mean it's a viable candidate for a motion control positioning system. For example, an induction motor and inverter controller can run from about 300 RPM to a base speed of 1,800. But positioning systems require speeds down to zero and often higher than 1,800 RPM. However, induction motors are ideal for centrifugal fans, conveyors, pumps, and mixers because they are relatively inexpensive, simple and easy to use, highly reliable, and vibration free. Additionally a peak overload capacity of 150% and direction reversal are possible. The controls have preset speeds and programmable I/Os.

Figure 1 – Induction motor torque vs speed



The torque/speed curve for a 1.0 hp induction motor shows constant torque up to base speed, but constant hp up to 3.5 times the base speed. The peak torque is within the normal ratings for a typical motor.

Figure 2 – Motor time to speed



The time to reach base speed varies considerably for various 1 hp motors. Each is driven in the constant current mode and the load = motor inertia. Vector motors take time to reach speed (400msec) while brushless servomotors are the faster by as much as a factor of eight (50msec).

Vector motors

However, don't dismiss induction motors for motion control altogether. Adding an encoder feedback device transforms it into a vector motor. This can be a candidate for positioning systems. Closing the loop around the encoder, controller, and motor lets the motor run down to 0 RPM with full torque. Vector motors with closed loop controls provide tight speed regulation and constant torque from 0 RPM to base speed, as shown in Figure 1. Operating in the constant horsepower mode lets the motor run up to three times the base speed. Controls include programmable features such as controlled acceleration, deceleration, etc.

A typical 1 hp vector motor with an inertia of 0.052 lb–in–sec^2 can accelerate to 1,800 RPM in about 0.4 seconds while operating in the current mode and with a load inertia equal to the motor inertia. See Figure 2 for comparison of motor technologies.

To provide the most reliable and efficient package, the vector motor should be designed with an efficient lamination, high temperature insulation materials, high efficient winding, and the electrical windings must include protection against high dv/dt rates (short rise times). The rapid dv/dt and voltage reflections will degrade electrical winding life. Vector motors should use spike resistant wire, which has been designed to provide protection for longer motor life and reduced downtime.

If the application has high inertial loads, a line regeneration vector control should be considered. Line regen controls save energy by returning the energy (power generated by the motor) back to the incoming power line. Also, because these designs operate at near unity power factor, they result in additional energy savings.

Servomotors

When a motion control system requires greater acceleration and velocity than is possible with an induction motor, a servomotor is a better choice. Servomotors can accelerate faster because they have a smaller diameter, lower inertia rotors. A 1 hp DC servomotor, for instance, accelerates two times faster than a vector motor when considering inertia only. However, when the additional starting or acceleration torque capability of the DC servomotor is considered, then the DC servomotor accelerates three or more times faster. Maximum speed for brush servomotors is about 6,000 RPM.

Brushless servomotors

Brushless servomotors are widely used. Brushless servomotors with their small packages offer higher speed, acceleration, torque, and lower inertia. Brushless servomotors can typically run to 10,000 RPM and higher. However, many applications don't take advantage of this capability.

Acceleration times for brushless servomotors depend on the magnetic design as it affects the rotor inertia. Some motors use ferrite magnets and others use rare earth such as neodymium or samarium cobalt. Ferrite brushless motors can accelerate almost10 times faster than induction motors, and rare earth motors 30 times faster.

Brushless servo motors are commercially available to about 15 hp. For applications that require greater horsepower, use an AC induction servomotor. These servomotors are rated to 60 hp. A typical 10 hp AC induction servomotor can accelerate two to four times faster than the standard AC induction motor due to its low rotor inertia. A comparison of technologies is shown in Table 1.

Table 1 – Comparing motor technologies

	10 hp		1 hp				
	AC Induction	Induction Servo	Inverter	Vector	DC Servo	Brushless	
						Ferrite	Rare Earth
hp Range	to 800	to 60	to 800	to 800	to 5	to 15	to 15
Speed	Typical	Higher	Typical	Typical	Higher	Higher	Highest
Speed Range	0 RPM to base speed	0 to 6,000	300 RPM to base speed	0 RPM to base speed	0 to 6,000	0 to 10,000	0 to 10,000
Starting Torque	150%	150 to 200%	150%	150%	200%	300%	400%
Inertia, $lb\text{-}in\text{-}sec^2$	0.78 [1]	0.186 [1]	0.052 [2]	0.052 [2]	0.024 [2]	0.0078 [2]	0.0025 [2]
Acceleration	Typical	Fast	Typical	Typical	Fast	Faster	Fastest

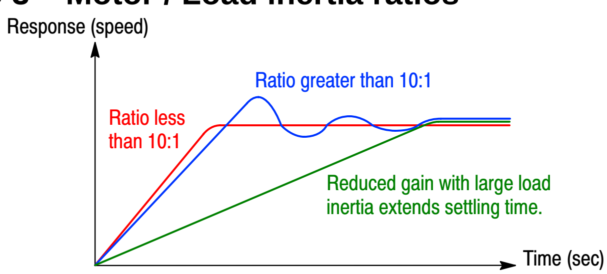
[1] For typical 10hp.

[2] For typical 1hp.

Improve response time

Lower load to motor ratios improve response times, reduce mechanical resonance, and minimize power dissipation. An inertia mismatch of greater than 10:1 can produce oscillations and extended settling times. To prevent overshooting and oscillations with very large mismatches, the control gain must be reduced. This extends settling time (Figure 3) and may not be acceptable for many applications.

Figure 3 – Motor / Load inertia ratios



A motion system with a load to motor inertia less than 10:1 can reach a set speed or move into position in less time than one with a ratio greater than 10:1. The higher load inertia causes oscillations and takes longer to settle out.

Changing gear ratios or the pitch on ball screws, and using larger motors are ways to reduce the inertia ratio. Also, special loop compensation can be installed, but this typically involves more expensive, custom designs, rather than standard off the shelf controls.

Mechanical resonance

Mechanical resonance can be defined with an equation which shows the relationship of inertia, frequency, and stiffness:

$$f = \frac{1}{2\pi}\sqrt{\frac{(J_L + J_M)\,K}{J_L\,J_M}}$$

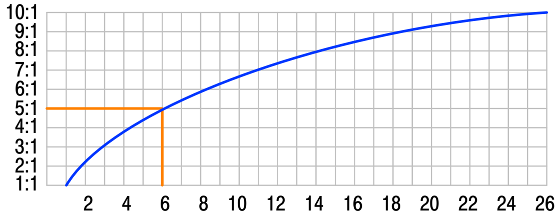
where J_L = load inertia, J_M = motor inertia, and K = the transmission stiffness. The frequency of the mechanical torsional resonance depends upon the stiffness, and the load inertia is inversely proportional to the mechanical resonance.

For best response, this frequency point should be outside the control bandwidth. Typically, this should be 5 to 10 times the loop bandwidth due to the rise time requirements. The easiest, fastest, and least expensive way to ensure that this point is sufficiently high is to use a high compliance coupling and a large gear ratio.

Minimize power

Another reason to check inertia ratios relates to power dissipation. Analyzing the equation for optimum versus non optimum dissipation produces the plot as shown in Figure 4. The graphic shows that a small deviation from optimum is not critical, however, as the deviation increases, the penalty becomes increasingly severe. As can be seen, the 1:1 ratio provides minimum power dissipation. For a mismatch of 5:1 the power rate increases more than six times. This also indicates additional current is required.

Figure 4 – Mismatched load power dissipation



Large inertia mismatches require higher current to drive the motor, thus they dissipate more power. For example, a mismatch of only 5:1 will dissipate six times more power, and it gets worse as the load inertia increases.