Motion control made easy

Day 2 Optimal design

Topics of discussion:
- Point-to-point motion
- Velocity profiles
- Coupling optimization
- Motor selection

In the previous issue we discussed the elements of a digital motion control system and how they work together. Today we will consider one of the more common types of motion, point-to-point, and establish a strategy for optimal system design.

Point to point motion

Almost every manufacturing and test process – from chipmaking to metal working – involves some type of point-to-point motion. For discussion sake, let's consider the operation of a typical circuit-board tester.

Before it can take its first measurement, a board tester has to get its probe into the right place. During operation, the probe must move from one point to another in an imaginary plane above the surface of the board. Although this motion has little to do with the actual function of testing, it can account for a significant portion of the machine's cycle time. Naturally each point-to-point move should be as fast as possible to increase overall throughput, which is where we begin to define what constitutes an optimal design.

To further define our design objective, we need to figure out what's limiting the time T it takes to make each move. In terms of physics, a point-to-point move equates to accelerating and decelerating a mass. The required force ($f = m \cdot a$) must be sustained over a given distance, necessitating a certain amount of current and heating (power dissipation) within the motor. Therein (motor heating) lies the physical limitation on T.

Now we can state our design objective more clearly: For a point-to-point motion control system where the load is required to move a given distance within a specified time, we need to design a system that minimizes temperature rise in the motor. This is achieved by:

- Driving the motor along the most efficient velocity profile
- Finding the best coupling ratio between the motor and load
- Selecting the best motor for the task.

Velocity profiles

To find the optimal velocity profile, assume a given motor must be rotated by an angle θ and come to a stop within T seconds. The profile that best meets the motion requirements while minimizing temperature rise in the motor is a parabola (Figure 1). For each move, the energy dissipation in the motor is

$$E = \frac{12rJ^2\theta^2}{K_t^2T^3} \qquad (1)$$

where r = armature resistance (Ω), J = moment of inertia (kg·m^2), θ = rotation angle (rad), K_t = torque constant (Nm/A), and T = motion time (sec).

Parabolic velocity, while optimal, is rarely used, however, due to the difficulty in generating it. Another disadvantage is that it requires high peak currents and causes large torque transitions at the beginning and end of each move.

A more practical velocity profile is the trapezoid, consisting of three time intervals. Although the time intervals can be set almost any way, the best case is when

Parabolic velocity profile

A parabolic velocity profile is the most efficient in terms of temperature rise in the motor but it is difficult to generate.

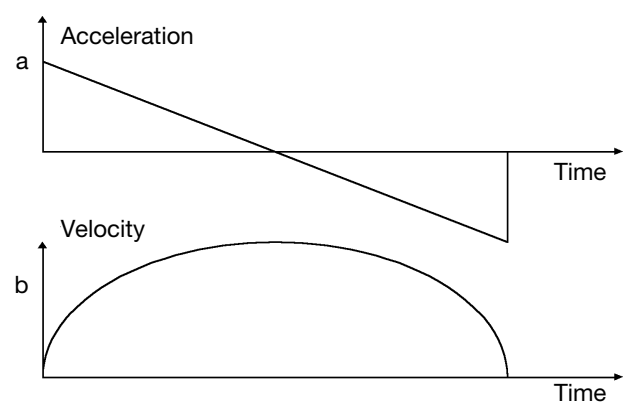

Figure 1

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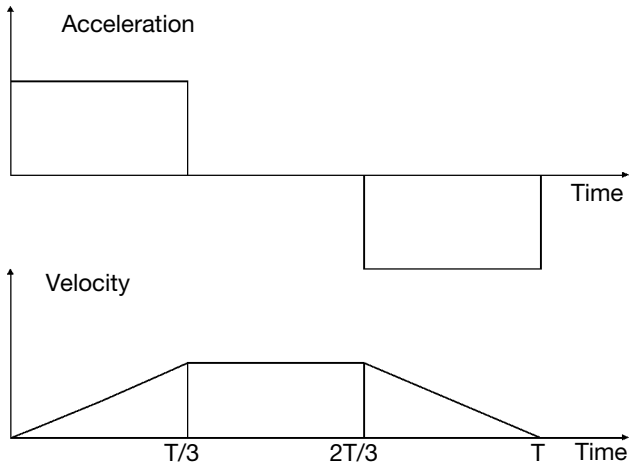
Trapezoidal velocity profile



Trapezoidal velocity profiles are common in motion control. Setting the time intervals to equal lengths minimizes temperature rise in the motor.

Figure **2**

all three intervals are equal (Figure 2). Here, the power dissipation per move is

$$E = \frac{13.5rJ^2\theta^2}{K_t^2T^3} \qquad (2)$$

which is a 12% increase over that of a parabolic profile.

It is interesting to compare parabolic and trapezoidal velocity to a triangular velocity profile (Figure 3). Here, the energy dissipation per step is

$$E = \frac{16rJ^2\theta^2}{K_t^2T^3} \qquad (3)$$

which represents a 25% increase over the optimal case.

Coupling optimization

The next thing to consider is the transmission device that couples the motor to the load, while also setting the velocity ratio. For a rotary load, a gear box or a set of pulleys that reduce motor speed by a fixed ratio are more than adequate. For linear motion, the coupling can be a belt and pulley.

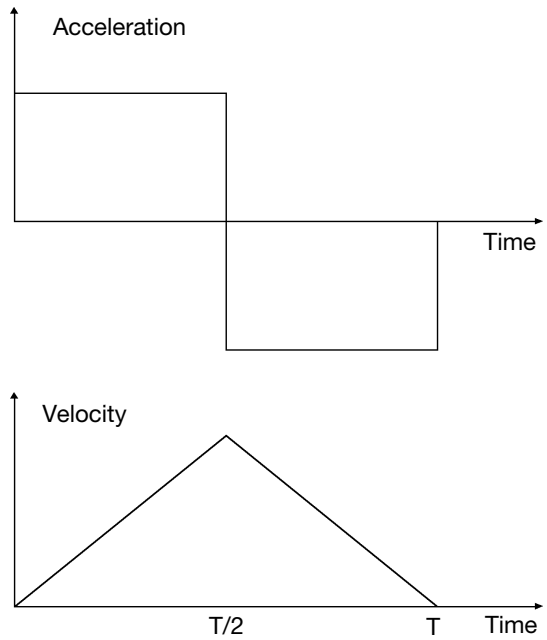
Selecting a coupling ratio that results in minimum power dissipation is fairly straightforward. Simply put, the optimal ratio is one that achieves an inertial match between the motor and load. In other words, the reflected load inertia (as seen by the motor) should equal that of the motor. Consider the following examples.

Case 1- Rotary load

Assume a rotary load of inertia J_{LO} coupled by a speed reducer with a ratio N to a motor with an inertia J_m. Due to the speed reduction, the effective load inertia as seen by the motor equals

$$J_L = \frac{J_{LO}}{N^2} \qquad (4)$$

Triangular velocity profile



Triangular velocity profiles cause a 25% greater temperature rise in the motor compared to the optimal (parabolic) case. Trapezoidal profiles, in contrast, cause a 12% increase compared to parabolic.

Figure **3**

The optimal reduction rate is when

$$J_m = \frac{J_{LO}}{N^2} \qquad (5)$$

meaning that the optimal reduction ratio is

$$N = \sqrt{\frac{J_{LO}}{J_m}} \qquad (6)$$

Case 2 - Belt and pulley

A load with a mass M is driven by belt and pulley, where the radius of the pulley is R.

Since the load inertia equals

$$J_L = MR^2 \qquad (7)$$

the optimum coupling is when

$$J_m = MR^2 \qquad (8)$$

and

$$R = \sqrt{\frac{J_m}{M}} \qquad (9)$$

Motor selection

The last step in the optimization process is to select the motor. Assuming that the coupling is optimized for the motor, the best motor is the one having the lowest value of

$$Q = \frac{rJ_mR_{th}}{K_t^2} \qquad (10)$$

where r = armature resistance (Ω), J_m = motor inertia (kg·m^2), R_{th} = thermal resistance (°C/W), and K_t = torque constant (Nm/A).

To illustrate the motor selection process consider the three motors in Table 1. Based on the value of Q, B is obviously the best choice for a motor.

Comparing motors

Motor	A	B	C
R (Ω)	4.0	2.0	1.8
Jm (kg·m2)	0.00012	0.0002	0.0005
Rth (°C/W)	3.0	2.2	1.8
Kt (Nm/A)	0.08	0.12	0.15
Q	0.225	0.061	0.072

Table **1**

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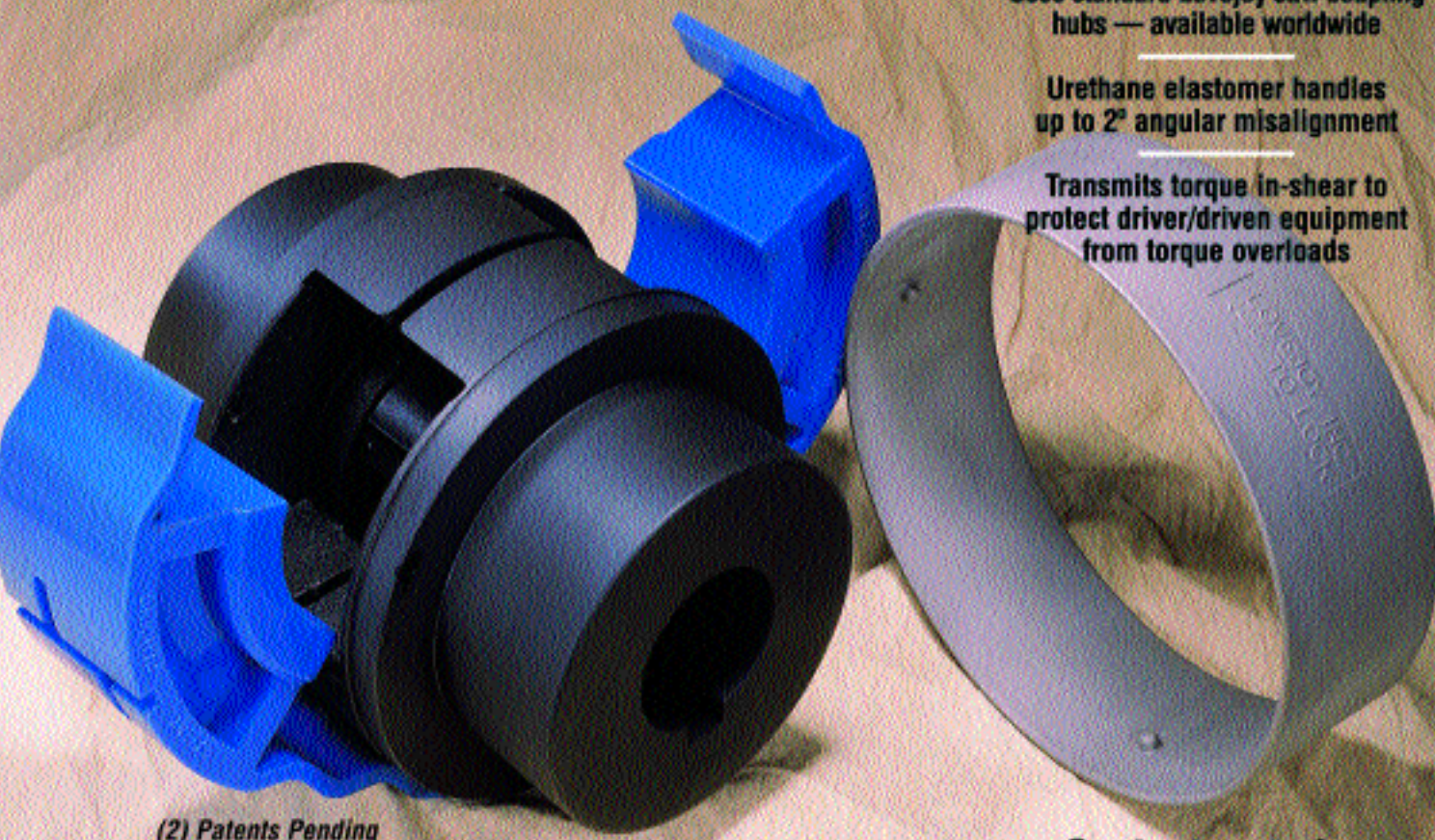

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