Tips on fitting the best motor

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Fitting the perfect motor to an application can be a complicated process. Here's a look at the steps an engineer took for a silk-screen printing application. Following these steps may help you.

A specialty manufacturer recently completed construction of a 16-station printer. Each station, dedicated to a different ink color, uses a brushless dc servo motor to drive an ink squeegee across the silk screen, Figure 1.

Each of the 16 squeegees attaches to its station carriage and disburses ink across the silk screen onto the printing surface. Linear bearings on the machine frame support each carriage, which is fastened between the pulleys. Two timing belts wrap around the pulleys. When the pulleys rotate, the timing belt pulls the carriage across the silk screen, Figure 2.

Pneumatic cylinders raise and lower the squeegee to the screen. The motor experiences the greatest load when the squeegee presses against the screen.

Determining criteria

The first steps are to determine required motor speed and the torque required by the application. Engineers placed a limit on the maximum carriage

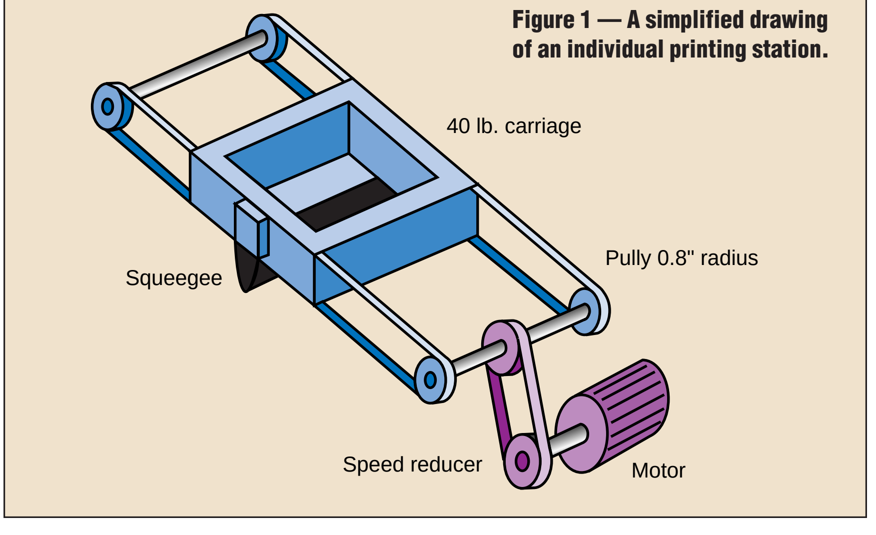

Figure 1 — A simplified drawing of an individual printing station.

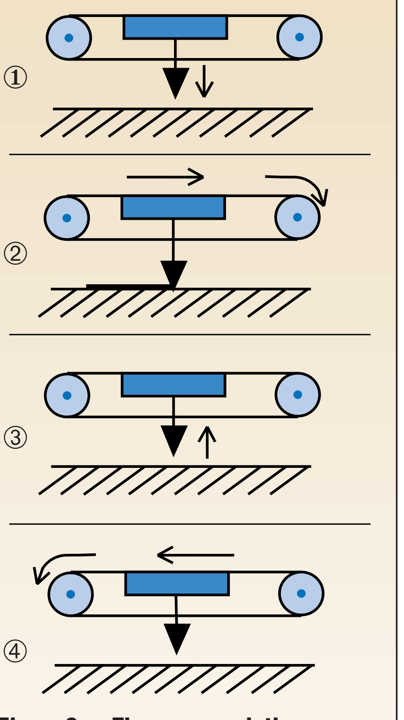

Figure 2 — The screen printing process.
1. **Squeegee goes down while carriage is at rest.**
2. **Carriage moves forward and spreads ink.**
3. **Carriage stops and squeegee comes up.**
4. **Carriage reverses and returns to starting position.**

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speed at 40 in./sec because if it travels too fast, the ink can't penetrate the screen and adhere to the print surface. The radius of the pulleys is 0.8 in.

Because this application uses a belt drive system, the motor speed was determined using the following equation:

$$N_m = \frac{9.55V_l}{r} \quad (1A)$$

Which resulted in:

$$N_m = 477.5 \text{ rpm} \quad (1B)$$

To determine the torque, six loading conditions must be defined:

- Acceleration torque.
- Deceleration torque.
- Friction torque with the squeegee up.
- Friction torque with the squeegee down.
- Breakaway torque with the squeegee up.
- Breakaway torque with the squeegee down.

Engineers measured the breakaway torque by attaching a torque wrench to one pulley on a prototype machine. The breakaway torque is 46 oz-in. with the squeegee up and 137 oz-in. with the squeegee down.

Friction torque was measured by connecting a dc motor with a known torque constant to one of the prototype's pulleys. They measured the motor's current while driving the load at a constant speed. The current measurement was then multiplied by the motor's torque constant. The friction torque was 35 oz-in. with the squeegee up and 116 oz-in. with the squeegee down.

The design engineers set the acceleration and deceleration times at 0.1 second. The carriage on their prototype weighs 640 oz, the four pulleys each weigh 3 oz, and the two belts together weigh 16 oz. The radius of the pulleys was 0.8 in. The acceleration torque, T_a, was then calculated:

$$T_a = \left[\frac{W_c r^2}{386} + \frac{nW_p r^2}{772} + \frac{W_b r^2}{386} + J_m\right]\frac{V_l}{rt_a} \quad (2A)$$

Solving, with:
W_c = 640 oz
r = 0.8 in.
n = 4 pulleys
W_p = 3 oz/pulley
W_b = 16 oz
J_m = 0 (because a motor hasn't been selected yet)
V_l = 40 in./sec
t_a = 0.1 sec

Then:
T_a = 549 oz-in.

The carriage is level, so gravity does not influence the load calculations.

Motor selection

With this approximation of the load's continuous and peak requirements, the next step was to select motor type.

The design called for a programmable positioning system to vary the stroke length of the squeegee instead of movable limit switches. The engineer chose to design his own digital motion control board to meet this requirement rather than buy "off-the-shelf." Using software, rather than manual control through limit switches, reduced down time between print runs.

To properly control position and velocity, the motor needed a servo amplifier with encoder feedback. For budgetary reasons, lower inertia rotor, and reduced maintenance needs the engineer chose a brushless dc servo system rather than an ac servo system with sinusoidal torque curves. The engineer also chose dc-powered amplifiers. This configuration gave him the flexibility to work with different power supplies.

Speed reducer

Because this is a servo application, the engineer had to choose a reduction ratio that matched motor inertia to load inertia. To calculate the gear ratio:

$$G = \sqrt{\frac{J_l}{J_m}} \quad (3)$$

Nomenclature

G = ratio of input speed to output speed
J_b = inertia of the belt, oz-in.-sec^2
J_c = inertia of the carriage, oz-in.-sec^2
J_l = inertia of driven load, oz-in.-sec^2
J_m = motor inertia, oz-in.-sec^2
J_p = inertia of the pulley, oz-in.-sec^2
n = number of pulleys
N_m = motor speed, rpm
r = radius, in.
t_a = time to accelerate, sec
T_a = acceleration torque, oz-in.
T_b = breakaway torque, oz-in.
T_f = friction torque, oz-in.
T_l = load torque, oz-in.
T_m = motor torque, oz-in.
V_l = velocity of the load, in./sec
W_b = weight of the belt, oz
W_c = weight of the carriage, oz
W_p = weight of the pulleys, oz-in.

To roughly approximate required motor size, the design engineer assumed the continuous torque rating of the motor should equal the measured friction torque, and the peak torque rating should equal the sum of the breakaway torque and the acceleration torque.

The engineer searched through catalogs and identified a brushless dc motor with a continuous torque rating of 151 oz-in., a peak rating of 610 oz-in. and a rotor inertia of 0.0215 oz-in.-sec. Solving for G:

$$G = \sqrt{\frac{J_c + J_p + J_b}{J_m}} \quad (4A)$$

or

$$G = \sqrt{\frac{\frac{W_c r^2}{386} + \frac{nW_p r^2}{772} + \frac{W_b r^2}{386}}{J_m}} \quad (4B)$$

Solving:
W_c = 640 oz
r = 0.8 in.
n = 4 pulleys
W_p = 3 oz/pulley
W_b = 16 oz
J_m = 0.0215 oz-in.-sec^2

$$G = 7:1 \quad (4C)$$

Timing belt and pulleys provide the reduction ratio. This arrangement avoids the backlash of a standard gearbox and the expense of a precision gearbox.

The load measurements and equations calculated earlier were adjusted for the assumed motor inertia and reduction ratio. Therefore:

$$N_m = \left(\frac{9.55 V_l}{r}\right) G \qquad (5)$$

$$= 4.77.5 \times 7$$

$$= 3342 \text{ rpm}$$

and

$$T_a = \left[\frac{W_c r^2}{386 G^2} + \frac{n W_p r^2}{772 G^2} + \frac{W_b r^2}{386 G^2} + J_m\right] \frac{N_m}{9.55 t_a} \qquad (6A)$$

Solving:
W_c = 640 oz
r = 0.8 in.
n = 4 pulleys
W_p = 3 oz/pulley
W_b = 16 oz
J_m = 0.0215 oz-in.-sec^2
N_m = 3342 rpm
G = 7,
t_a = 0.1 sec

$$T_a = 154 \text{ oz} - \text{in.} \qquad (6B)$$

Speed reducers perform a dual function; simultaneously they reduce the output speed of the motor and multiply the torque output. With a given load, the torque required of the motor is reduced by a factor equal to the gear ratio:

$$T_m = \frac{T_l}{G} \qquad (7)$$

Using this equation, the measured loads were re-adjusted:

T_f, squeegee up = 35 oz-in./7 = 5 oz-in.

T_f, squeegee down = 116 oz-in./7 = 16.6 oz-in.

T_b, squeegee up = 46 oz-in./7 = 6.6 oz-in.

T_b, squeegee down = 137 oz-in./7 = 19.6 oz-in.

Optimizing the motor size

Because of the cyclical nature of this application, optimum motor sizing required calculating the rms torque. If the rms torque is less than the continuous rating of the selected motor, a smaller motor might be more appropriate for each printing station.

However, if the rms torque is greater than the continuous rating of the selected motor, then a larger motor should be chosen.

The table of torque/time data points displays the adjusted torque values calculated earlier, Table 1. The data points were used to calculate the rms torque using the following equation:

$$T_{rms} = \sqrt{\frac{\sum (T_i^2)(t_i)}{\sum t_i}} \qquad (8A)$$

$$T_{rms} = 57.6 \text{ oz} - \text{in.} \qquad (8B)$$

The calculated rms torque was much lower than the continuous rating of the selected brushless dc motor so the design engineer went back to the manufacturer's catalog. He identified a smaller brushless dc motor of the same basic design that was rated 81 oz-in. continuous and 270 oz-in. peak. This motor was perfect for the application. The motor manufacturer later supplied samples with thermocouples in the motor winding, which confirmed that the motor would not overheat even under worst case loading conditions.

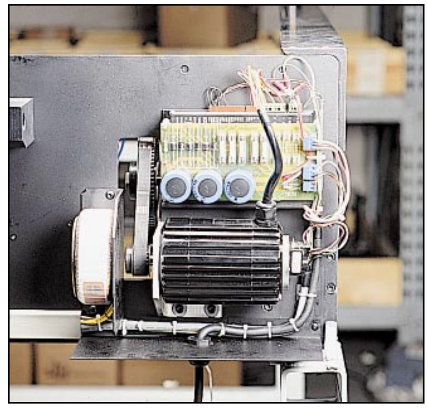

Figure 3 — Selected motor for the application.

Table 1 — Torque/time data points

Data point, i	Description	Time change, ti	Torque, Ti
1	Motor at rest with squeegee down	0 sec.	0 oz-in.
2	Motor accelerates to full speed with squeegee down	0.1 sec	174 oz-in.
3	Motor runs at full speed with squeegee down	0.8 sec	17 oz-in.
4	Motor decelerates to stop with squeegee down	0.1 sec	137 oz-in.
5	Motor at rest while squeegee raises	0.5 sec	0 oz-in.
6	Motor accelerates to full speed in reverse direction with squeegee up	0.1 sec.	161 oz-in.
7	Motor runs at full speed in reverse with squeegee up	0.8 sec	5 oz-in.
8	Motor decelerates to stop with squeegee up	0.1 sec	149 oz-in.
9	Motor at rest while squeegee lowers	0.5 sec	0 oz-in.

For more information on fitting a motor to an application, call 1-800-7BO-DINE for a free brochure, "Motor and Gearmotor Selection Guide," from Bodine Electric Company. The eight-page brochure is a step-by-step guide to help design engineers select the ideal motor for an application.