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Latest developments in voice coil actuators

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Need smooth motion, high speed and acceleration, or tight servo control? Voice coil actuators, providing rotary or linear motion, may be the solution you need. Here's a look at choosing the right one for your application.

Voice coil actuators are direct-drive electric motors that provide limited linear or rotary motion. They are often used in applications requiring proportional and tight servo control, such as mirror and lens positioning in optical systems, high-accuracy machine tool positioning, precision valve control in medical and industrial devices, and linear drives for cryogenic coolers and other pumps.

These non-commutated actuators use a permanent-magnet field assembly with a coil winding to produce a force proportional to the current applied to the coil. Both linear and rotary versions meet the acceleration, frequency actuation, and linear force or torque-versus-stroke output requirements needed in many linear and rotary motion applications. Some of the linear versions, Figure 1, provide continuous force (stall) from 1.15 to 9.7 lb, with a peak force for 10 sec from 2.5 to 32.5 lb. Some rotary versions provide continuous torque (stall) from 4.05 to 480 oz-in, with 10-sec peak torque from 11 to 1,536 oz-in.

Figure 1 — Linear voice coil actuator with the copper coil wound around a ferromagnetic cylinder. Two wires connect to the coil leads, shown above the coil winding.

A linear voice coil actuator consists of a two-terminal tubular coil of wire in a radially oriented dc magnetic field, Figure 2. Permanent magnets embedded on the inside diameter of a ferromagnetic cylinder produce a constant field. The side of the magnets that faces the ferromagnetic cylinder has the same polarity as the cylinder. The opposite side of the magnets facing the coil has the opposite polarity. Completing the magnetic circuit is an inner core of ferromagnetic material along the axial centerline of the coil that is joined at one end to the permanent magnet assembly.

The actuator is a single-phase device. It operates using the cross product of a magnetic field and a current flow through the coil winding. Applying voltage across the two coil leads generates a current in the winding. This current produces a proportional force on the coil, causing the coil to move axially along the air gap. The direction of the current flow in the wire determines the direction of movement. The speed of actuation depends on the magnitude of the current flowing through and the voltage applied to the coil.

From a straight line to a curve

If you "flatten" a linear voice coil actuator, Figure 2, from a round tube to a flat tube, then bend the two ends to form a

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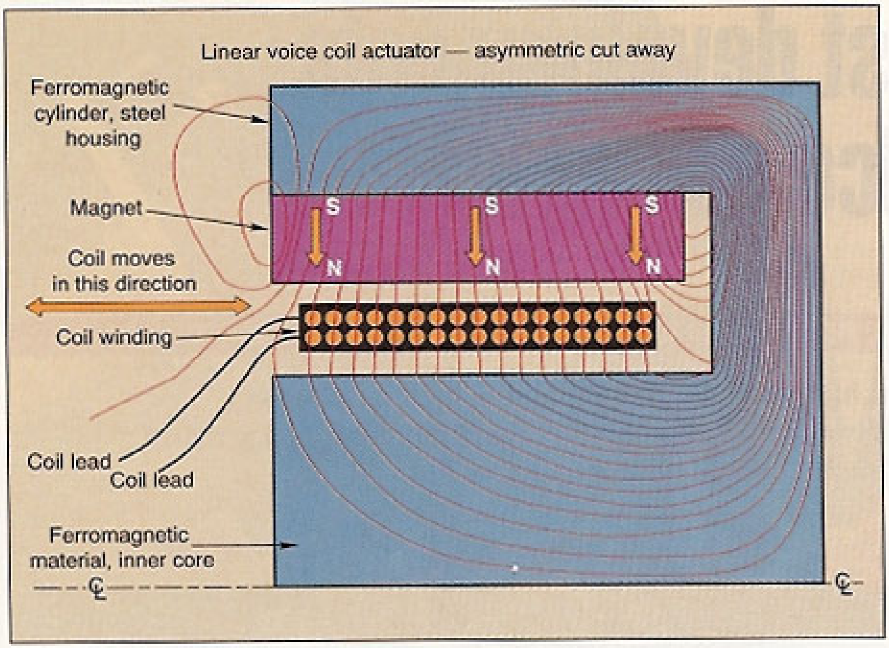


Figure 2 — Side view cutaway of the flux plot of a linear voice coil actuator. The actuator consists of a ferromagnetic cylindrical steel housing with an inner core of the same material. Mounted to the inside diameter of the housing, opposite the inner core, are permanent magnets. Between the magnets and the inner core, within an air gap, is a tubular coil of wire. Applying voltage across the two coil leads generates a current in the winding. The cross product of the magnetic field and the electrified coil produces a force that causes the coil to move axially along the air gap.

planar arc, you will have a rotary voice coil actuator, Figure 3A and 3B. Rotary voice coil actuators generate force identical to their linear counterparts. However, the ratings are in units of torque, instead of force, because force is generated along the circumference of an arc.

Material composition

Both types of actuators are available in several materials, depending on required system performance, operating environment, manufacturing considerations, and cost. Typically, the coil is wound with copper or aluminum-magnet wire coated with a thin polymer film for electrical insulation.

The most common permanent magnet materials are hard-magnetic ferrites, Neodymium Iron Boron, and Samarium Cobalt. The steel flux return, or "back-iron" steel, can be any high permeability ferromagnetic material, and need not be laminated. The fasteners and bonding agents must be able to survive the required operating environment.

Control

In precise servo control applications, voice coil actuators require feedback for closed-loop control. Many position, velocity, and force transducers can function as feedback devices. Most common are optical encoders, contact and magneto-resistive potentiometers, LVDT's, and load cells.

The actuator's power supply must have sufficient current to meet an application's force requirements. It must have a high enough voltage rating to overcome the back EMF at maximum coil velocity and the resistive and inductive voltage drops across the winding.

The coil resistance (Ohms) and force sensitivity (Newtons/Ampere) of these actuators can be impedance matched to most dc power supplies. Common amplifiers include H-bridge and PWM types.

Mechanical systems

Voice coil actuators are usually sold as a set consisting of the magnet and coil assemblies. The minimum air gap clearance between these assemblies is 0.010-0.015 inches; sometimes more if required by the application. The user must provide a guidance system for full range of motion and to prevent the coil winding from rubbing against or crashing into the magnet assembly. In most cases, the load is connected to the coil assembly because the coil has a lower mass (often by an order of magnitude) than the field assembly. In cases where the load is sensitive to applied heat, it can be connected to the magnet assembly.

The preferred guiding means for the linear version consists of linear bearings or bushings combined with steel shafts, though flexures are often used in short-stroke applications. If needed, actuator manufacturers can make shaft-bushing combinations an integral part of the actuator. It is important to keep the friction levels of the guidance system low to ensure the smooth response characteristics of these actuators. Rotary voice coil actuators typically use shaft-ball bearing guidance systems identical to those of conventional electric motors.

Choosing a rotary voice coil actuator

Rotary voice coil actuators are frequently used in gimbal assemblies for flight hardware systems. These applications often require low weight and a small "footprint." Rotary voice coil actuators offer these features plus low inertia and high torque output over a limited angle of operation.

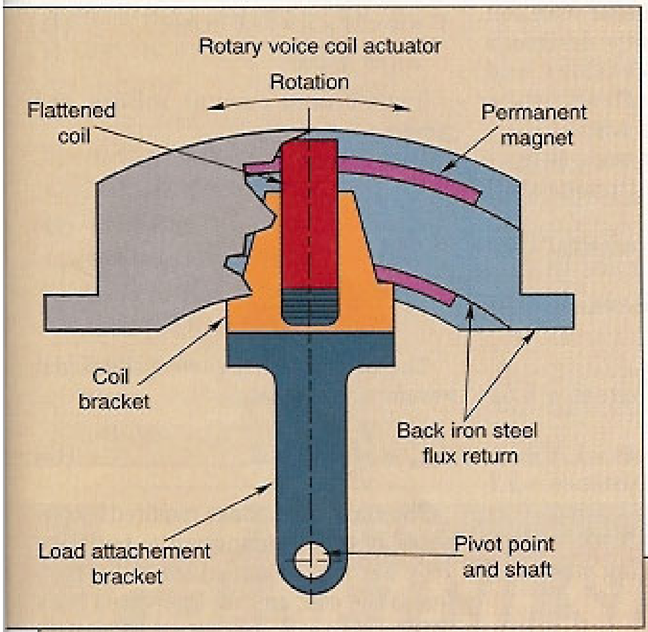
Several calculations are necessary to choose the right actuator. In this example, Figure 4, the engineering parameters are:

- Voltage available, 12 Vdc.
- Total angular travel of inner axis is 40 deg; outer axis is 20 deg.
- Move time of inner axis is 32 msec; outer axis is 140 msec.
- Load and friction torque of inner axis is 3 oz-in.; of outer axis, 9 oz-in.
- Assume a polished aluminum mirror weight of 3.4 oz. Dimensions of the mirror

are 1/4 by 3 by 3 in. with a slight curvature.

- Mirror inertia about the inner axis of rotation is 0.0066 oz-in.-sec^2
- Inner axis aluminum support weight is 17 oz.

Four series of calculations are needed: Inner axis acceleration torque, inner axis winding verification, outer axis (or complete assembly) acceleration torque, and outer axis winding verification. Only the inner axis acceleration torque will be described to illustrate the process.



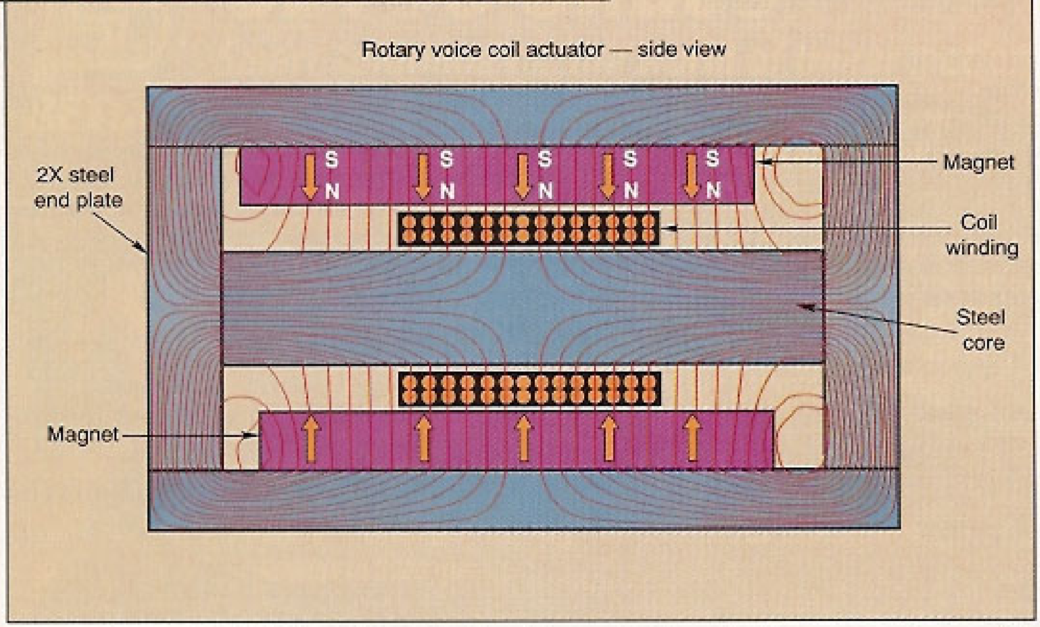


Figure 3A (top) — A rotary voice coil actuator. The rotary version is created by flattening a linear voice coil from a round tube to a flat tube, then bending the two ends to form a planar arc. A bearing assembly or mounting arm attaches to the lever point. The actuator moves within some subset of the actuator arc.

Figure 3B (bottom) — Side view flux plot of a rotary voice coil actuator.

Inner axis acceleration torque

The mirror load inertia is known, but actuator coil inertia and acceleration rate are not. Determine the acceleration rate for the angular displacement requirement during a triangular move, Figure 5, using equations 1 and 2:

$$V_{TRI} = \frac{\left(\frac{40^\circ}{360^\circ}\right)(2\pi)}{32} \tag{}$$

$$= 21.8 \text{ rad/sec} \qquad (1)$$

$$V_{max} = 2V_{TRI}$$

$$= 2 \times 21.8$$

$$= 44 \text{ rad/sec} \qquad (2)$$

In a triangular move profile, though, acceleration occurs during the first half of the move, or in this case, in 16 msec.

α = acceleration rate = (44 Rad/sec)/(16 msec) = 2750 Rad/sec^2.

Ignoring coil inertia for the time being, determine the torque required to accelerate the mirror:

$$T_\alpha = J_m \times \alpha \qquad (3)$$

$$= .0066 \times 2750 = 18 \text{ oz} - \text{in.}$$

This torque must be available for deceleration, too. In addition, the continuous duty operation calls for an actuator with a continuous torque rating of at least the required 18 oz-in.

To check the effect of coil inertia on the overall torque requirement: assume an actuator with a coil inertia of approximately 8.5 X 10^{-5} oz-in.-sec^2 about an axis perpendicular to the plane of motion, through the center of mass in the coil. In this application, the coil will not rotate about its own center of mass. Instead, it will rotate about an axis parallel to its own axis and two inches away. Equation 4 determines the inertia of the coil, relative to the axis of rotation — the rotational axis of the mirror — using the mass of the body, m, and the distance, d, between the two parallel axes.

$$J_d = J + md^2 \qquad (4)$$

$$J = 8.5 \times 10^{-5} + \left[\frac{.44}{386}\right] \times (2)^2$$

$$= .0046 \text{ oz - in. - sec}^2$$

The total acceleration torque requirement is:

$$T_\alpha = (J + J_m) \times \alpha \qquad (5)$$

$$= (.0046 + .0066) \times 2750$$

$$= 31 \text{ oz} - \text{in.}$$

a value higher than the 18 oz-in. initially calculated.

The total peak torque, T$_p$, requirement is therefore the total acceleration torque, T$_\alpha$ plus the load and friction torque from the engineering parameters, 3 oz-in., which equals 34 oz-in. Using the recommended 20% safety margin, this example calls for an actuator with a peak

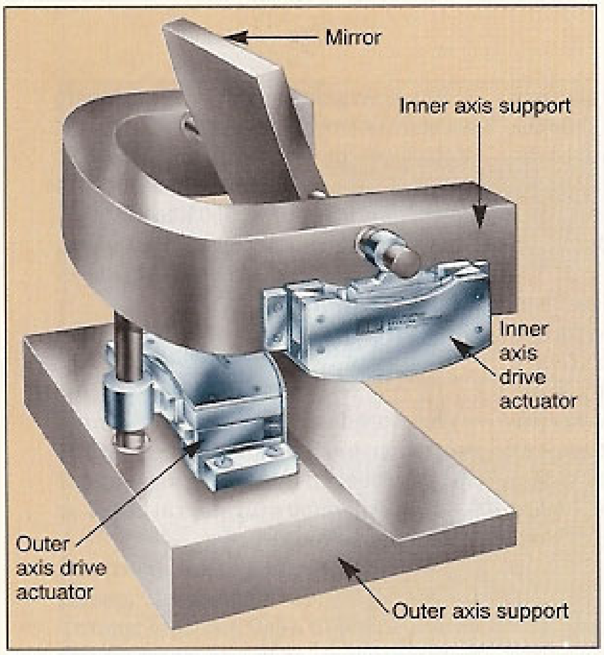


Figure 4 — Gimbal assembly showing two rotary voice coil actuators. The inner axis drive actuator turns the mirror. The outer axis drive actuator turns the mirror assembly.

and continuous torque rating of:

Peak = 1.2 (34 oz-in.) = 41 oz-in.
Continuous = 1.2 (31 oz-in.) = 37 oz-in.

Calculating the outer axis acceleration torque follows a similar procedure.

Choosing a linear voice coil actuator for an X/Y stage application

A designer wants to sinusoidally oscillate a 1.0 lb load over the maximum attainable frequency for two linear displacements:

$D_1 = \pm .050$ in. and
$D_2 = \pm .450$ in.

The customer's envelope dimensions are a 2.75-in. maximum outer diam and a 5.00-in. maximum length with the coil fully extended.

Customer requirements and specifications:

- Power supply voltage = open
- Power supply current = open
- W_l = Load mass = 1.0 lb
- Duty cycle = 10%
- Maximum OD = 2.75 in.
- Maximum length = 5.00 in. (fully extended)
- Stroke, case 1, (D_1) = ± .050 in. = .100 in. = case 2, (D_2) = ± .450 in. = .900 in.
- Maximum frequency = unknown

The chosen linear voice coil actuator meets the designer's envelope dimensions and stroke requirements, while providing high force.

- F_p = Peak force = 60 lb
- F_{cs} = Continuous stall force = 19.4 lb
- K_F = Force constant = 4.8 lb/A
- R = Coil resistance = 2.4 ohms
- Stroke = ± .500 in.
- K_B = Back EMF constant = 6.51 V/(ft/s)
- W_c = Coil assembly mass = 1.20 lb
- V_m = Coil thermal resistance = 2.2 C/W = ϑ

Determining the moving mass and acceleration:

Moving mass:

$$W_m = W_c + W_l \tag{6}$$
$$= 1.2 + 1.0 = 2.2 \text{ lb}$$

Acceleration:

$$G = \frac{F_p}{W_m} \tag{7}$$
$$= \frac{60}{2.20} = 27.3$$

Determining the maximum frequency and velocity:

Case 1: D_1 = .100 in., G = 27.3 G

Frequency:

$$F = \frac{1}{2\pi}\sqrt{\frac{386.1 \times G \times 2}{D_1}} \tag{8}$$
$$= \frac{1}{2\pi}\sqrt{\frac{386.1 \times 27.3 \times 2}{.100}} = 73 \text{ Hz}$$

Velocity:

$$V = \pi F D_1 \tag{9}$$
$$= \pi \times 73 \times .100 = 22.9 \text{ in./A}$$
$$= 1.91 \text{ ft/sec}$$

Case 2: D_2 = .900 in., G = 27.3G

Frequency:

$$F = \frac{1}{2\pi}\sqrt{\frac{386.1 \times 27.3 \times 2}{.900}} = 24 \text{ Hz} \tag{10}$$

Velocity:

$$V = \pi \times 24 \times .9 = 67.9 \text{ in./sec} \tag{11}$$
$$= 5.65 \text{ ft/sec}$$

To determine current, voltage, and power:

Peak current:

$$I_p = \frac{F_p}{K_F} \tag{12}$$
$$= \frac{60}{4.8} = 12.5 \text{ A}$$

The current will assume a sinusoidal waveform, such that:

$$I_{rms} = \frac{I_p}{\sqrt{2}} = 8.84 \text{ A} \tag{13}$$

The maximum voltage required is composed of three components: resistive drop across the coil, inductive drop across the coil, and the generated back EMF:

$$V_{\max} = V_p + V_L + V_B$$
$$= I_p R_H + L\frac{di}{dt} + K_B \tag{14}$$

Also calculate the increase in coil resistance due to heating, R_H. Assume a worst case coil temperature of 155 C and a 25 C ambient:

$$R_H = R\left(1 + .00393 \times \Delta T\right) \tag{15}$$
$$= 2.4\left(1 + .00393\left(155 - 25\right)\right) = 3.63\Omega$$

Case 1: velocity = 1.91 ft/sec

L(di/dt) = 15 V (conservative estimate)

$$V_{\max 1} = \left(12.5 \times 3.63\right) + 15 + \left(6.51 \times 1.91\right)$$
$$= 73 \text{ V} \tag{16}$$

Case 2: velocity = 5.65 ft/sec

L(di/dt) = 5 V (conservative estimate)

$$V_{\max 2} = \left(12.5 \times 3.63\right) + 5 + \left(6.51 \times 5.65\right)$$
$$= 87 \text{ V} \tag{17}$$

The amount of power dissipated in the

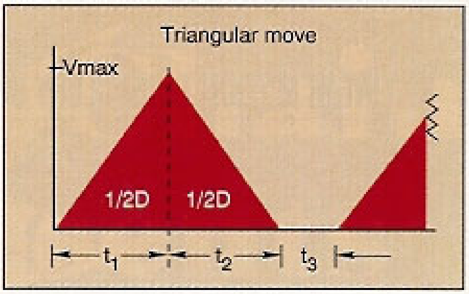


Figure 5 — Point-to-point positioning of an actuator can be trapezoidal or triangular moves. In this gimbal assembly example, the designer chose to use a triangular move. Therefore, the acceleration rate for the angular displacement required during a triangular move is found through equations 1 and 2.

coil is from I_2^2R heating only:

$$P_d = I_{rms}^2 \times R_H \qquad (18)$$

$$= 8.84^2 \times 3.63 = 284 \text{ W}$$

The final coil temperature should be less than the 155 C maximum rating for the winding:

$$\Delta T_{coil} = P_d \times duty \times \vartheta_{TH} \qquad (19)$$

$$= 284 \times .10 \times 2.2 = 62.4°\text{C}$$

$$T_c = 25°\text{C} + \Delta T = 87.4°\text{C} \qquad (20)$$

If this article was helpful, ***circle 411*** *on the reader service card.*

For more information on rotary or linear voice coil actuators from BEI Sensors & Systems Co., Kimco Magnetics Div., ***circle 412*** *on the reader service card.*

Nomenclature

For selection of a rotary voice coil actuator:

α = load angular acceleration rate, Rad/sec^2.
J = rotational inertia, oz.-in.-sec^2
J_d = Inertia of a body about any axis, oz.-in.-sec^2
J_{L+C} = sum of the actuator coil and reflected load inertias, oz-in.-sec^2.
J_m = mirror inertia, oz-in.-sec^2.
K_B = Back EMF constant, (V/(ft/sec))
K_t = Torque that is the product for a given current input, oz-in./A.
R_C = resistance at 25 C, Ω
R_H = Resistance at maximum coil temperature, Ω
T_α = acceleration torque, oz-in.
T_J = Torque needed to accelerate a body about an axis located at its center of mass, oz-in.
T_{max} = Maximum coil temperature, C
T_p = total peak torque, oz-in.
V_B = Back emf generated by moving coil, V.
V_C = Force producing voltage, V
V_{el} = electrical losses, V
V_L = Inductive voltage drop across the coil,V
V_{max} = rated operating speed of actuator, in./sec
V_{TRI} = average speed of actuator required for a specified triangular move, in./sec.

For calculations for selection of a linear voice coil actuator:

F_{cs} = continuous stall force, lb
F_p = Peak force, lb
I_p = Current, A
K_B = Back emf constant, V/(ft/sec)
K_F = Force constant, lb/A
P_d = Dissipated power, W
R = coil resistance, Ω
W_c = Coil assembly mass, lb
W_l = load of coil assembly mass, lb
W_m = Coil assembly mass, moving mass, lb
ϑ_{TH} = coil thermal resistance, c/W