Ball-Bearing Motor

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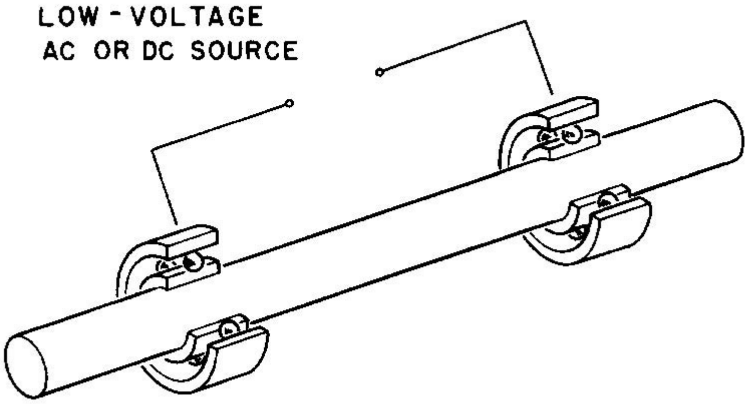
1 Problem

Discuss the principle of operation of a so-called ball-bearing motor, a popular form of which is sketched below.[1]



Note that this motor is not self-starting; the axle must be given an initial angular velocity, of either handedness, after which the motor can sustain rotary motion, if the current (AC or DC!) is large enough.

2 Solution

The discovery/invention of the ball-bearing motor is attributed to Milroy [1]. It has been discussed several times, with conflicting explanations [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. This solution is a much simplified version of that given in [6].

Because the motor is weak, it is helpful to reduce friction on the axle by connecting the high-current lead to the outer races of the ball bearings, as shown above. However, I believe that this is not required in principle, and that it is simpler to analyze the interaction of a rotating, current-carrying axle with a single roller bearing whose axis is fixed,[2] as shown on the next page.

The axle has angular velocity $\mathbf{\Omega}$, and the angular velocity $\boldsymbol{\omega} = -(a/b)\mathbf{\Omega}$ of the roller has the opposite sign, where a and b are the radii of the axle and bearing, respectively. The axial current $\mathbf{I}_a$ in the axle generates azimuthal magnetic field $\mathbf{B}_a$. The Lorentz force $\mathbf{v}_b \times \mathbf{B}_a = (\boldsymbol{\omega} \times \mathbf{r}_b) \times \mathbf{B}_a$ on the conduction electrons in the roller leads to a current $\mathbf{I}_b$ that

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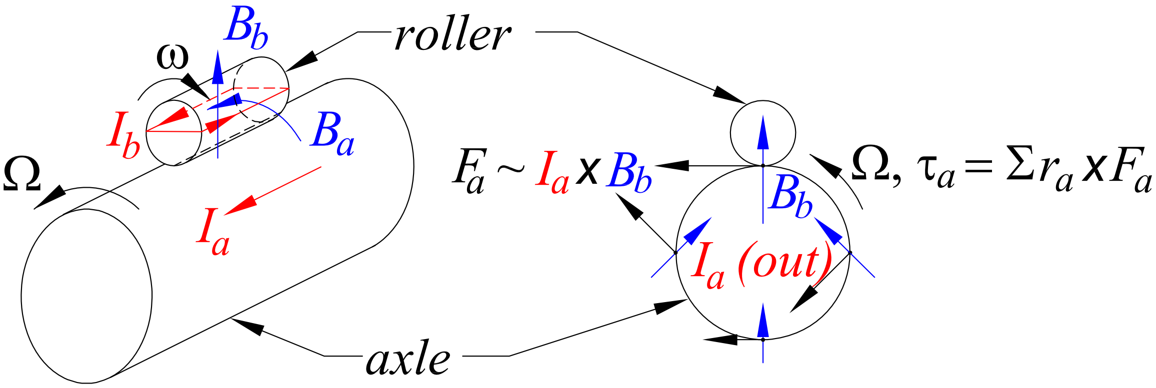
[1] Numerous videos of variants of this device are available on YouTube.

[2] In practice, the roller (or ball) bearings are encased in a "race" that can rotate with respect to both the axle and the outer sleeve. Then, the axes of the roller bearings move azimuthally, which complicates the motion, but which does not change the essence of the analysis given below.

circulates around the roller. This current $\mathbf{I}_b$ (which is proportional to the conductivity σ of the roller) generates a (dipole) magnetic field $\mathbf{B}_b$ that is generally perpendicular to the axle inside the latter. The consequent magnetic forces $\mathbf{F}_a \propto \mathbf{I}_a \times \mathbf{B}_b$ on current filaments in the axle vary over the axle,[3] but the strongest force is near the line of contact of the axle and roller, where the force exerts a torque on the axle that has the same sense as the angular velocity $\mathbf{\Omega}$, thereby increasing (or at least maintaining against friction) the angular velocity of the axle.[4]



The magnitude of the torque scales (in Gaussian units) as $\sigma \Omega I_a^2 / c^4$ where c is the speed of light.

An alternative configuration is for the axle to be held fixed while the bearings rotate about it. If the bearing race were fixed to the outer sleeve of the bearing, then a torque (clockwise in the above figure) on the bearings could be transmitted to the latter, providing another type of motor. This configuration would result in friction between the bearings and the bearing race, which might limit the utility of the motor.

The ball-bearing motor is another example of a system that is usefully described by saying that magnetic forces/torques do work [14].

References

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[3] The current filaments have helical form due to the rotation of the axle, but their azimuthal component does not lead to an azimuthal torque.

[4] Another argument notes that parallel currents attract, such that a current filament along the top of the axle is attracted to the left current around the bearing, and repelled from the right current. The net force on the current filament is to the left, and the reaction force on the bearing is to the right.

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