Ball-Bearing Motor

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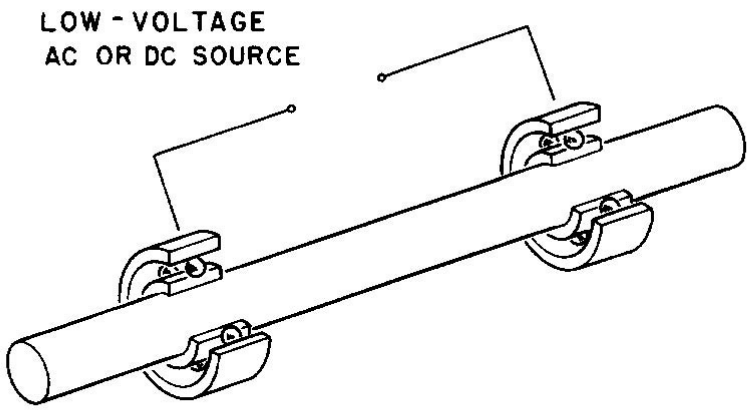
1 Problem

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 in general; the axle must typically 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, 14, 15, 16, 17, 18, 19, 20, 21, 22].[2,3] This solution is a much simplified version of that given in [9].

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

[2]All authors except Marinov [7] suppose the torque to be electromagnetic, whereas he states (without supporting argument) that the torque results from thermal expansion of the bearings (which effect does not obviously produce a torque).

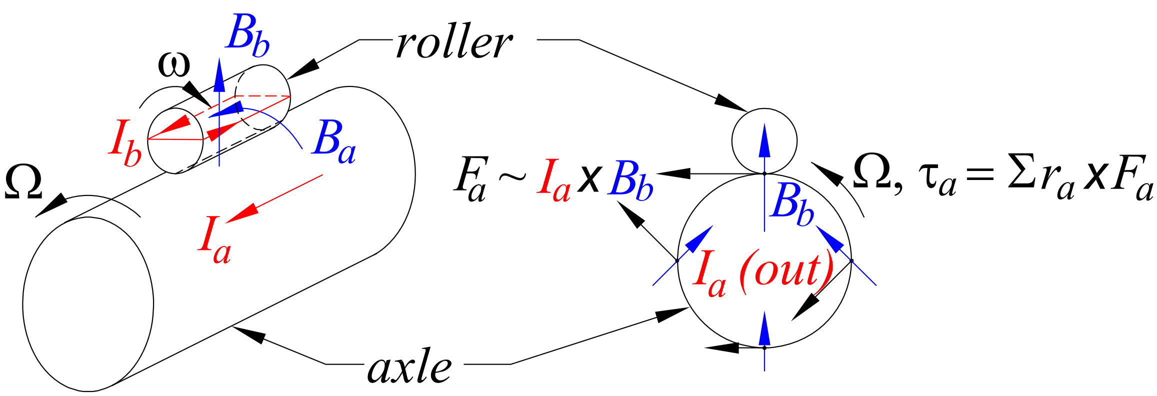
It is generally agreed that the first attempt at an electromagnetic explanation, [2], was wrong. Also, the explanation in [10] was later retracted by its author.

[3]Refs. [6, 17, 20, 21] associate ball-bearing motors with the "Huber effect", after [23]. However, Huber considered a kind of railgun in which the crosspiece, a sphere or cylinder, rolled along tracks, propelled by the Lorentz force on the current in the crosspiece. If the crosspiece is to roll rather than slide, there must be a torque, due to static friction between the crosspiece and the rails, to rotate the crosspiece as its axle moves down the track. As the axis of a ball-bearing motor is fixed, this frictional "Huber effect", which constraint force does no work, is not relevant here.

The earliest report of a sphere rolling on electrified tracks is on p. 195 of [24]. For some general comments about railguns, see [25].

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[4] with a single roller bearing whose axis is fixed,[5] as shown below.

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 circulates around the roller.[6] 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,[7] 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.[8]



The magnitude of the torque scales as $\sigma\Omega I_a^2/c^4$ (in Gaussian units), where c is the speed of light. This behavior was observed in the experiments of [21]. Since the conductivity σ is or order $1/c$, the torque scales as I^2/c^3, whereas in more practical (SI) units the torque scales as I^2/c^2. Either way, this confirms that a ball-bearing motor is a very weak device.

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

[4] The axle could be either a hollow or a solid conductor.

[5] 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.

[6] When there is no rolling, there is no current I_b, and no Lorentz force $\mathbf{I}_a \times \mathbf{B}_b$ on the axle. Hence, the motor cannot start from rest.

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

[8] 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.

the bearing race, which might limit the utility of the motor.

In yet another variant (thanks to Alexis Bacot), the axle is fixed and nonconducting, and the current enters and leaves the system through lead wires attached to the inner races of the bearings; the outer races of the two bearings are attached to a conducting cylinder that rotates along with them. The currents in the lead wires generate the magnetic field $\mathbf{B}_a$*, which has sufficient radial field component on the bearings that the above analysis still applies.*

The ball-bearing motor is another example of a system that is usefully described by saying that magnetic forces/torques do work [27].[9]

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