Electric Motor Design

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Abstract:

Electric motors are versatile devices capable of converting electricity into kinetic energy. Electromechanical batteries use the technology behind electric motors in order to sustain the kinetic energy. The energy can later be discharged as electricity, generating power entirely from motion, free of dependence on chemicals. In order to find alternate energy storage methods, simple example of an electromechanical battery was designed from an electric motor with an added flywheel. For devices in which power input is intermittent rather than constant, steady and stable power storage that does not decay with each use is a necessity that can be satisfied by electromechanical batteries. The design took advantage of common power supplies, easily obtained materials, and three-dimensional printing technologies.

1. Introduction:

In today’s domestic setting, society has implemented numerous technologies into its everyday life that are dependent on the use of a motor; electric fans, blenders, and microwaves are just a few examples of an extensive list. For obvious reasons, it is inconceivable to power many of these technologies with an internal combustion engine: the heat and exhaust from such motors, along with their large size, render combustion motors useless in many enclosed settings, be it residential or industrial. As a counterpart to internal combustion engines, electric motors are an excellent power source. These motors are not limited by size, have no direct harmful emissions, and emit minimal heat. Electric motors can be found in products of all sizes: washing machines, air conditioning units, computer cooling fans, forklifts, and compact disk drives all utilize this technology.

The National Aeronautics and Space Administration (NASA) has played a significant part in extending the boundaries of the applications of electric motors. NASA began experimenting with flywheels thirty years ago, looking for more efficient ways to store energy to be utilized by its satellites. Currently, NASA utilizes mechanical flywheels—circular objects with high moments of inertia—that store kinetic energy with a half-life of 15 years and that act as power storage units. NASA’s flywheel technology provided motivation for the practical application of an electrical motor and its design: create an electric motor modified with a flywheel in order to create an electromechanical battery.

While the majority of people are familiar with electrochemical batteries, such as lithium ion and lithium polymer batteries, electromechanical batteries are much less common in everyday life. Although not portable, electromechanical batteries offer a clean energy storage method that can be used both on large and small scales, and that can be easily recharged and repaired if necessary. The goal of the project was to optimize the capabilities of a small-scale
electromechanical battery and test its storage capacity, energy half-life, and electrical output capabilities.

2. Background:

An electric motor is a device that converts electrical energy into mechanical energy. There are two main subsets: alternating current (AC) motors, which are usually brushless, and direct current (DC) motors, which are either brushless or use carbon brushes. DC electric motors have two parts: a rotating section, called a rotor, and a stationary section, called the stator. In this design of a DC brushed motor, the rotor is wrapped in coils of wire that are energized with electrical current, forming electromagnets, and surrounded by permanent magnets that induce a constant magnetic field. Brushed DC motors use the relationship between the active wire and the magnetic field to convert electricity into rotational motion.

Electric current is the movement of electrons through a wire, while resistance is the opposition to current in a wire. The two are related through Ohm’s Law:

$$V = iR$$

This is defined with $i$ as the current, $R$ as the resistance along the path taken by the electrons, and $V$ as the voltage or the potential difference. Ohm’s Law is very important in the efficacy of electric motors because it affects the power a motor can output depending on the wire used—a relation demonstrated through the equation:

$$P = iV$$

Power ($P$) is the product of current and voltage.

When a current passes through the wire, the flow of electrons induces a magnetic field that interacts with the magnetic field surrounding the rotor. The interaction between the different magnetic fields, called Lorentz Force, exerts a torque perpendicular to the direction of the current on the rotor. Lorentz Force is defined as:

$$F = Bi$$

$F$ is the force acting on the rotor, $B$ is the magnitude of the magnetic field, and $i$ is the current running through the coils of wire. The total torque exerted on the rotor due to Lorentz Force is defined by the equation:

$$\tau = Ki = LNrBi$$

The torque ($\tau$) is related to the length of the wire ($L$), the number of coils ($N$), the radius of the motor ($r$), the magnitude of the constant magnetic field ($B$), and the current passing through the wire ($i$). $K$ is a constant specific to the motor that characterizes its strength in torque generated per Ampere of current.

The work generated by an electric motor can be stored as mechanical energy. This type of energy is sustained in a rotating
object as momentum, which remains reserved in the object due to its tendency to resist acceleration. This tendency is known as moment of inertia. As the object gains rotational velocity, its rotational momentum increases. Therefore, a rotating object with a high angular momentum and high moment of inertia will continue to rotate for an extended length of time, unless acted upon by some outside force, most commonly air resistance and friction. Moment of inertia is mathematically represented as:

\[ I = mr^2 \]

\( I \) is the resistance to acceleration, \( m \) is the mass of a point on the object, and \( r \) is the radius, measured from the point to the object’s axis of rotation. The energy that can be stored in a rotating object with a given moment of inertia (\( I \)) is

\[ E = \frac{1}{2} I \omega^2 \]

where \( \omega \) represents the rotating object’s angular velocity. The rotor gains angular momentum until it reaches a maximum angular velocity, known as its steady-state velocity. When the source of electricity is cut off, the flywheel will continue to spin the rotor due to its moment of inertia. Limitations to the angular velocity and storage half-life develop because of friction and because of an adverse application of Lorentz Force. Since the coils are moving within a magnetic field, a current is developed inside the coil’s wires opposite the current that was being supplied by the power source. When the force being applied, \( F_{\text{applied}} \), and the force being generated, \( F_{\text{generated}} \), are equal, the rotor cannot gain any more angular velocity (\( \omega \)). The motor’s maximized \( \omega \) at that point is known as its steady-state velocity, \( \omega_{ss} \).

\( \omega_{ss} \) is dependent on the \( K \) constant of the motor, the resistance in the wire, the friction generated at the bearings that hold the rotor in place, and the voltage applied to the motor. \( \omega_{ss} \) can be calculated using:

\[ \omega_{ss} = \frac{Ki}{\beta} \]

\( K \) is the motor’s constant, \( \beta \) is a coefficient of friction, and \( i \) is the current being supplied to the motor. However, since the current supplied to the motor varies with the gauge of wire used in the coils, it was necessary to derive the steady-state velocity without having a concrete \( i \) value. Using the equation for resistance, \( R = \frac{v}{i} \), the torque generated by friction \( \tau_f = \beta \omega \), and the torque generated by the motor \( \tau = Ki = LrNi \). The steady-state velocity equation was then algebraically derived, where \( K \) is a constant specific to the motor, \( R \) is the motor’s net resistance, \( \beta \) is a coefficient of friction, and \( V_{\text{applied}} \) is the voltage supplied to the motor by the power source. In order to maximize \( \omega_{ss} \) and thereby maximize energy, the \( K \) value of a small motor with a limited \( V_{\text{applied}} \) should be set equal to \( \sqrt{R\beta} \). Due to imperfections in the motor design, such as the presence of different frictions and imperfect coil packing, the predicted \( K \) value of the motor is slightly less than the ideal \( K \).

3. Analysis and Design:

3.1 Design:
Of the many concepts of physics that have to be taken into consideration while designing an electric motor, \( \tau = LrNB_i \), is one of the most important. The most variable aspect of this equation is the wire, as the strength of the magnetic field and the current were both limited. Therefore, strategically choosing wire material and gauge was an extremely important step in the design process. Since the torque of the motor is directly proportional to the number of coils and length of each coil past the magnet, it was important to create a design that would allow a large amount of wire to be used. A large amount of wire correlates to a large number of loops which would maximize the torque of the motor. This particular quality of the motor played a monumental part in the design. Rather than a conventional design, in which wire is wrapped in coils and laid flat against a cylindrical rotor, the best design for this particular motor was a cylindrical rotor with raised pieces that would act as housing for the wire. This way, the wire would be wrapped around the housing instead of laying flat against the rotor, allowing for more wire to fill the space.

Another essential quality that comes as a result of this unique rotor design was the creation of electromagnets. An electromagnet is created when a current runs through a wire, which generates a magnetic field. The magnetic fields created by the permanent magnets and the electromagnets attract and repel each other. Because of that, the polarity of the coils on the rotor had to be changed with the aid of brushes in order to allow the magnetic energy to be converted into kinetic. The brushes are attached to one side of the rotor. The rotor has eight copper foil contacts, separated by small gaps, through which current passes. As the brushes pass over the copper foil, the polarity of each contact oscillates thus allowing the entire mechanism to rotate.

Wire has a circular cross-sectional area. Because circles are one of the least efficient shapes to pack into a two-dimensional area, it was important to find the densest arrangement of wires in order to estimate a maximum number of wraps. According to Thue’s Theorem of Circle Packing, the highest packing density for a lattice of circles is achieved when the centers of the circles are arranged hexagonally. The density of circles in a theoretical two-dimensional space is defined by:
\[ \eta_h = \frac{\pi}{2\sqrt{3}} = 0.9069 \]

Theoretically it is only possible to fill approximately 91% of the available space with wire, regardless of the wire’s gauge\(^3\). The next step was choosing the best gauge of wire for this specific motor. Larger wire allows more current to pass with less resistance, but the number of loops in each coil is severely diminished. Smaller wire has the inverse effect. However, due to a limit on available current, it was determined that wire with a smaller gauge would be most effective, as this design would utilize the wire’s current capacity to its best potential while allowing space for a greater number of loops in each coil.

3.2 Materials:

The majority of the motor was crafted on a 3D printer. The 3D printer uses acrylonitrile butadiene styrene (ABS), an amorphous terpolymer that is both tough and rigid\(^5\). A material’s toughness represents its resistance to break under stress, and its rigidness represents its resistance to flexing. Another popular plastic, polylactic acid (PLA), was an option for the motor. However, PLA is less tough and less rigid than ABS, meaning that parts made out of PLA are more likely to bend out of shape, but less likely to break\(^6\). At the speeds at which rotors typically rotate, the bending of parts is just as dangerous as the breaking of parts. For these purposes, a tough, rigid plastic is the better choice for the rotor than a flexible, strong plastic\(^4\).

The magnets chosen were 4 x 1 x \(\frac{1}{4}\) inch grade N45 neodymium magnets with a maximum field strength of 1.38 Tesla. Neodymium magnets, the most widely used rare-earth magnets, consist of an alloy of neodymium, iron, and boron. They are the strongest type of permanent magnets made\(^7\). Neodymium magnets reach magnetic saturation at about 1.6 Tesla, and are typically commercially available with 1.3 Tesla.

When choosing the motor’s flywheel, one of the most crucial characteristic to...
consider was the object's moment of inertia. Wheels model a particular instance of moment of inertia, involving a thin circular hoop of radius \( r \) and mass \( m \). Rather than summing up the masses of each point on the spokes and the radii of each point, the mass of the spokes can be considered negligible when compared to the mass of the outer wheel. In this case, the wheel’s moment of inertia can be found by the previously stated moment of inertia equation. Interestingly, bicycle wheels are designed to take advantage of this exact inertial phenomenon. For this motor, the best option available was a bicycle wheel with the largest diameter, because a larger diameter gives the flywheel a larger moment of inertia. The wheel that was bought to act as a flywheel was the front wheel of a bicycle, with a twenty-seven inch diameter and a weight of 6.2 pounds, giving it a moment of inertia of 0.661 kg/m\(^2\).

Insulated copper wire, copper foil, and carbon brushes are necessary for motors to function. The coated copper wire was used for the motor’s coils and to attach the motor’s power supply to its brushes. The copper foil acted as contact between the leads of the coils and the brushes, with either the positive leads or the negative leads of two adjacent coils soldered to a foil patch. The brushes were eight small apparatuses containing a brass wire inserted into a small block of graphite.

The entire magnet housing-rotor body will be fit into a polyvinyl chloride (PVC) unit for support. This unit has a six inch internal diameter and is a seven inch long piece of PVC piping with two PVC caps, one on either side, creating a cylindrical housing body for the motor. In both caps, a hole will be drilled to hold the ball bearings, and several smaller holes will route the wires connecting the carbon brushes to the power source.

3.2 Limitations:

The design of an electric motor requires compromises due to the relationship of different aspects that tailor the capabilities to specific purposes. The most variable aspects of the equation \( \tau = L N r B i \) are the resistance and its relationship to the number of loops in each coil. Therefore, the wire will only fill ninety-percent of the available area, no matter the gauge. A larger wire will allow more current with less resistance, but the number of loops will be severely diminished. Smaller wire has the inverse effect.

Since wires have inversely related attributes to motor efficiency, the decision on which wire gauge to use was based on resource limitations. For example, only 12 Volts of power was available for a power supply, in order to replicate an easily accessible power source. The most optimal size for the motor to stay within the limitations is a twenty-four gauge wire. While the resistance of the wire presents it as the worst option, the power source for the motor was limited to a total of 20 Amps of current with 12 Volts, the limit on available current forced extra consideration. The twenty Amps will be divided among eight different coils, so each coil is only experiencing 2.5 Amps. With this restriction, a large wire’s current carrying capabilities would not be utilized, while majority of the thin, twenty-four gauge wire will be near its max. It is far more beneficial to maximize the number of loops in each coil. The need to compromise surfaced in decisions about structure as well. A rotor with a small radius will rotate with a higher angular velocity as shown by the equation \( \omega = \frac{v}{r} \) where \( v \) is the velocity and \( r \) is the radius, but one with a larger radius ensures a higher moment of inertia to store the kinetic energy longer. These decisions were made by taking into
consideration certain restrictions on the project. During the design of the motor, the machining processes were restricted to a Filament Deposition Machining (FDM) three-dimensional printer to develop individual motor parts. The size of the components was restrained to the size of the print bed which was 6 inches by 4 inches by 6 inches. In order to follow the goals of the project, the larger radius was chosen because the moment of inertia increases, contributing to the kinetic energy storage longevity.

3.3 Project Obstacles

The original goal was to create a working prototype of an electromechanical battery; however the team’s lack of access to appropriate resources created many obstacles for the project. Without access to a machine shop, the team attempted to use a 3D printer to create the custom parts of the motor. Regrettably, many failed prints set the project far behind schedule. When a more efficient printer became available, time was too short to complete the prototype of the device. The team hopes to complete the project in the near future.

4. Results and Discussion:

Determining the overall efficiency of the final prototype involved testing several different qualities of the motor. Since the main goal of the motor was to act as an electromechanical battery, one of the most significant measurements to make is the power output, because this value is key in establishing the success of the motor as an energy storage device. The energy storage was theoretically calculated to be 305.5 Joules. To determine the power output, the motor will be connected to a voltmeter that measured the Voltage generated by the rotations of the rotor.

Another important test of the motor’s efficiency is measuring the rotations per minute completed by the flywheel. The higher amount of rotations per minute completed by the flywheel, the higher energy stored from the motor. Using the theoretical steady-state angular velocity, the rotations per minute were found to be 425.

One more essential measurement is the half-life of the flywheel. The value of the half-life shows how long the motor will theoretically be able to store energy, or the length of the life of the motor as a battery. The half-life was mathematically calculated to be 5.42 hours. This will be physically tested at a later date by measuring the velocity and the friction of the motor at a variety of time intervals and then taking those values and plotting them on an exponential decay curve where the decay constant in the matched equation of the graph was the coefficient of friction.

5. Conclusions:

5.1 Verdict

Overall, the project produced designs of an electromechanical battery that promise positive results. The team will be able to build a motor that functions as a working electromechanical battery. While the spinning of the flywheel may not continue for an exuberant amount of time due to limited conditions of the design project, this research will show how the basics of electromechanics work, and that mechanical energy can be stored and converted into electrical energy, and flywheels are a viable technology for energy storage that should be explored in the future. When the results are found, it will be possible to see how efficient these motors can be. With better equipment, in more effective conditions, a motor like this would make an excellent battery.
5.2 Future Plans

Designing an electromechanical battery from an electric motor helped open ideas for the future of energy. While small-scale models are unlikely to be proven economically competitive, the creative nature of the project goal opened many people’s minds to future possibilities. The major application of the flywheel technology for the future is storage for inconsistent renewable energy resources. Solar power, for example, only generates power when the panels are exposed to the light of day. During the night, when electricity demands for lighting and other needs continue, there is a lack of power supply. Any considerable storage method needs to be able to handle constant discharge and recharge. Many battery systems lose storage potential with time and those systems would need to be replaced often, but the mechanical nature of the flywheel allows for a theoretically infinite number of recharges. Many improvements on the electric motor would be necessary to make the technology effective and reliable. For instance, one of the largest factors to a loss in angular velocity after the power source has been removed is friction. By eliminating friction between the rotor and the rotor’s housing, the half-life of the electromechanical battery would be greatly increased. A plausible way to accomplish this is by use of magnetic bearings. With the addition of magnetic bearings, higher rotational speeds would be plausible and friction would be heavily reduced. Magnetic bearings allow support for the system without physical contact so any mechanical wear is heavily diminished, allowing the flywheel system to have a longer operational life. If the system were to be placed in a vacuum chamber, friction would be further reduced and the sustainability of the kinetic energy would be extended. One final improvement for the motor in order for it to be applicable on a larger scale would be to detach the flywheel to prevent Lorentz Force from continuing its effects after the motor has reached its maximum angular velocity. After the power supply is removed, the system will continue to spin due to inertia and current will be generated in the wire. If the flywheel is detached, it will spin free of these reducing forces, and sustain stored kinetic energy even longer. The drawback of this particular method is the retrieval of energy. The rotor needs to be powered to spin at the same rate as the flywheel or high levels of energy will be lost in the reattaching of the rotor.

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7. References


