

Project 1
Instrumented Beakman's Motor

Beakman's Motor (shown on the TV show *Beakman's World*) makes a very interesting little project. We use this motor in the ECSE course *Fields and Waves I* because it involves some fundamental electromagnetic concepts. It is also used in *Mechatronics* because it is a simple example of a complex electromechanical system. There is some excellent background information and some construction hints at the sites listed on the links page: <http://hibp.ecse.rpi.edu/~connor/education/EILinks.html#Proj1>. It is possible to specify several project goals for this motor, depending on its application. Here, you are asked to make the motor go as fast as possible.

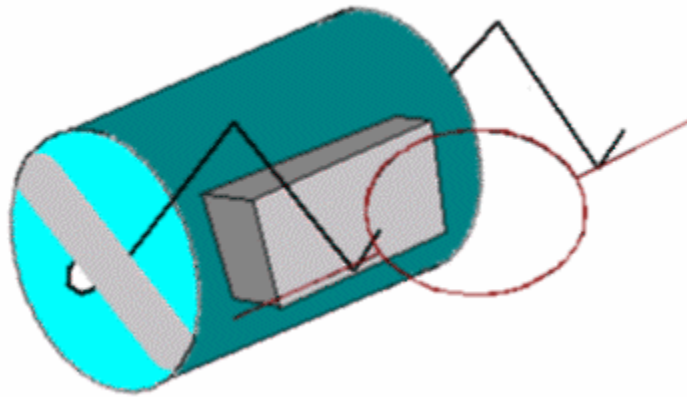


Figure 1 -- Beakman's Motor

Note the basic components – a D-Cell battery, a rubber band, two paper clips, a ceramic permanent magnet and a coil of wire.

Materials Required:

- One D-Cell Battery
- One Wide Rubber Band
- Two Large Paper Clips
- One or Two Circular Ceramic Magnets (or equivalent)
- Magnet Wire (the kind with enamel insulation)
- One Toilet Paper Tube (or paper tube)
- Fine Sandpaper and wooden block for sanding surface

In the appendix of this handout we have included a list of what we expect from you for this project. This includes a basic task list, a list of the required appendices for your report, and a description of the report format. Please follow these requirements carefully.

Part A -- Background and Theory

The basic principles of motor operation are quite simple. Each time the coil spins through a single revolution, the commutator turns the current on for half of the cycle and off for half of the cycle. While the current is on, the coil becomes an electromagnet. This magnet is either attracted to, or repelled by, a permanent magnet attached to the battery that powers the motor. By properly orienting the commutator, the coil is given a little push each time it goes by the magnet and it will continue to spin. While this description is adequate to explain generally how the motor works, it is not so useful for actually designing a motor.

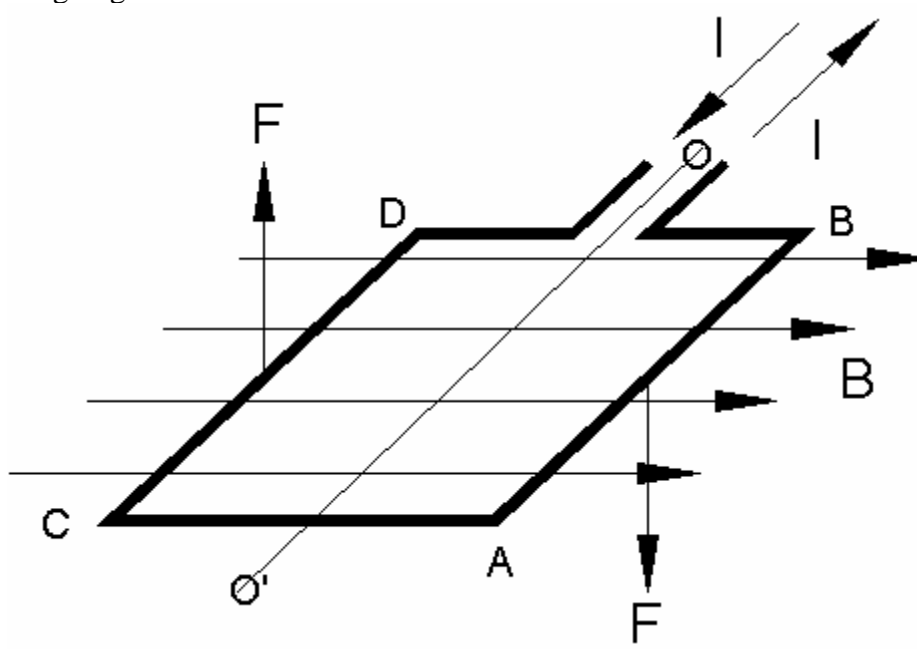


Figure 2 – Current carrying wire in a magnetic field

A better model involves the forces between current-carrying wires and magnetic fields. A current carrying wire experiences a force due to a magnetic field in a direction perpendicular to both the wire and the field, as shown in the figure 2 above. In the most fundamental terms, we express this force as $\vec{f} = \vec{J} \times \vec{B}$, where f is the force density, J is the current density in the wire (J is I divided by the area of the wire) and B is the magnetic field. Most simply, this expression can be written as $\vec{F} = I\vec{L} \times \vec{B} = ILB \sin \alpha$, where I is the current, L is the length of the wire (This can be expressed as a vector by multiplying it by the unit vector in the direction of the current flow), and α is the angle between the wire and the magnetic field. There is quite a good discussion of the principles behind the DC motor on the links page under the title “Principles behind the DC motor” from Micro Mo Electronics in Clearwater, FL. (The figure above comes from this web site.) It will be useful to read over this material to see how to optimize your motor designs. Where would the magnet be located in the figure showing the forces?

In this experiment, you will build a simple motor coil, attach it to a power source, and make it spin. You will make a simple commutator (that turns the electromagnet on and

off) by sanding off only half of one of the motor leads. As the motor spins, the commutator forces the coil to appear alternately like an open circuit and a wire (with resistance and inductance). When the sanded portion of the lead is in contact with the cradle, the coil looks like an inductor, the current flows through the coil, and this creates the electromagnet. At this time, it interacts with the stationary magnet on the battery. When the un-sanded portion of the motor lead is in contact with the cradle, the coil looks like an open circuit, the current is off, and the coil no longer acts as an electromagnet. What forces are still acting on the coil when the current is off? What would happen to the coil if the current was always flowing?

This circuit seems simple: a coil, a switch (the commutator), and a power source. However, there are many factors that influence how the coil spins. The coil itself is an inductor and a resistor. As you know, its properties depend on the type of wire used, the diameter of the coil, and the number of turns. In addition, the connection wires used (if any), the paper clips and the battery itself all have some resistance. Other factors also influence your motor. Energy lost to air drag and coil wobble will look like resistance to the circuit. Also, as the coil spins past the magnet, a small current will be induced in the coil. This current will be in the opposite direction to the applied current. Depending on the relative size of the resistances and inductances, the net effect of all this will either look like an inductance or like a resistance.

Part B – Building your Initial Design

B-1. Building a Motor

The projects in this course typically involve building an initial design that we give you, improving the design, and comparing the initial and final results. For the initial design in this project, you will build a motor using the instructions in a video clip from an old television series, called “Beakman’s World”. Try to build this first motor with characteristics that match the motor in the video as closely as possible. When assembled, it should look much like the motor pictured in figure 1. Here are some basic instructions:

1. Take about 3 feet of 26 gauge magnet wire.
2. Wind it around a cardboard toilet paper tube seven times. Leave 2” leads.
3. Sand the coating off of one lead completely.
4. Sand the coating off one side of the other lead. (This is your motor commutator.)
5. Bend the paper clips into cradles and attach them to the battery with the rubber band.
6. Place two magnets on the battery (NOT THE POWER SUPPLY).
7. Add your motor and make it spin.

If it doesn’t work, make sure your sanding job is complete and the motor is well balanced.

B-2. Measuring the Frequency

By monitoring the current to or voltage across the coil, the frequency of the motor can be determined. Place the oscilloscope leads across the coil (one on each paper clip). Note that your motor is spinning very slowly compared to most electrical signals. You will need to adjust the scope by hand. Think of how many rotations per second your motor seems to spin at and set the scale accordingly. When the 'scope is adjusted correctly, you should see a sequence of square pulses, that may look something like figure 3 below.

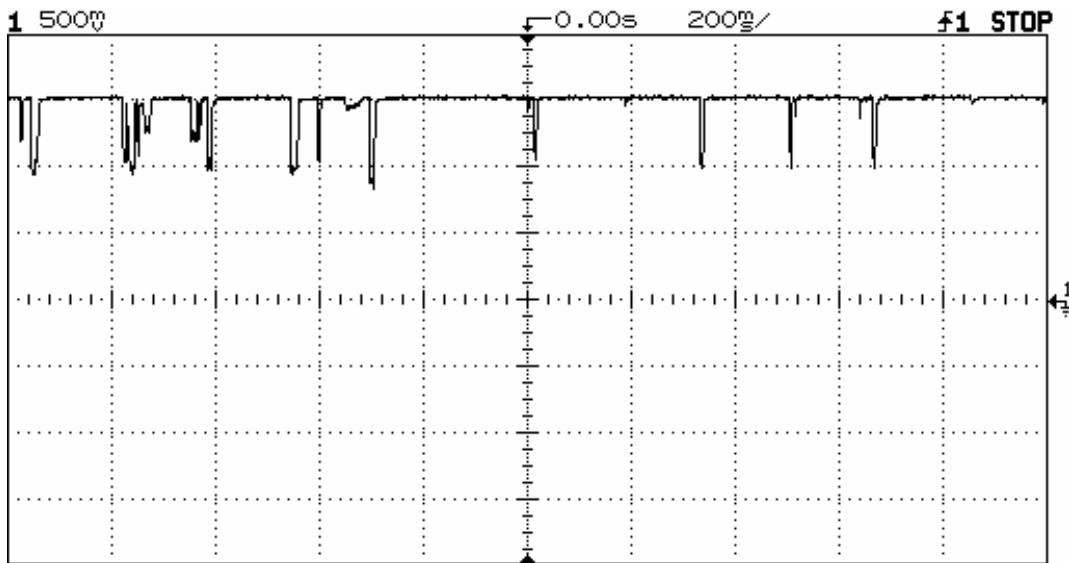


Figure 3 – Poor data sample (note inconsistent frequency)

Note that the maximum voltage is the open circuit voltage of around 1.5 volts. This is the voltage of your battery. When the motor spins to the point where the coating has been sanded off, contact is created, it no longer looks like an open circuit, and the voltage drops. As the motor turns more, the contact goes away, the coil looks like an open circuit again, and the voltage goes back up to 1.5V. If your voltage ends up between -1.5V and 0, switch the polarity of the leads on the paper clips.

The data above, would not be considered very good because of the irregularity of the pulses. In order to get better data, you will want to make sure your leads are sanded very well and that your motor is well balanced. These improvements should give you data that looks more like figure 4.

For your initial design, you may not be able to get data quite so regular. Adding springs (as described later) will improve this. If the spinning is sufficiently regular, the frequency measurement capability of the oscilloscope can be used to get the frequency. You can also calculate the frequency by hand. Average over several pulses to get an accurate measurement.

To determine the frequency of the data in figure 4, count the number of cycles shown and divide by the time. In figure 4, there are a total of 30 cycles over 2 seconds (200ms*10 divisions) for a frequency of 15 Hertz.

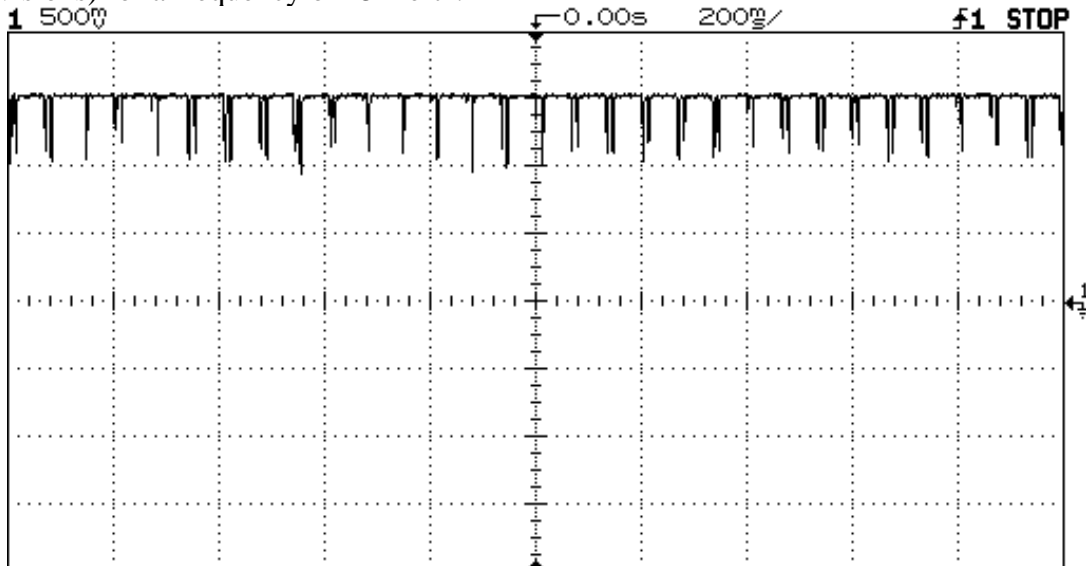


Figure 4 – Good data sample (note consistent frequency)

B-3. Measuring the Characteristics of your Battery

Although batteries are rated to output a particular voltage (such as 1.5V), the actual voltage will vary slightly from the specifications (like any other electrical component). Also, (like any other power supply) batteries have a small internal impedance. In order to accurately create the circuit diagram for the initial motor, you need to find the characteristics of your battery.

You cannot measure the internal impedance of the battery directly because it is inside the battery. You also do not know the exact voltage that the battery is putting out. It is rated at 1.5V, but since it is a real device, it probably is not putting out exactly 1.5V. In order to measure the voltage and resistance of the battery, we can create two circuits, measure the output voltage of each, and solve two equations in two unknowns.

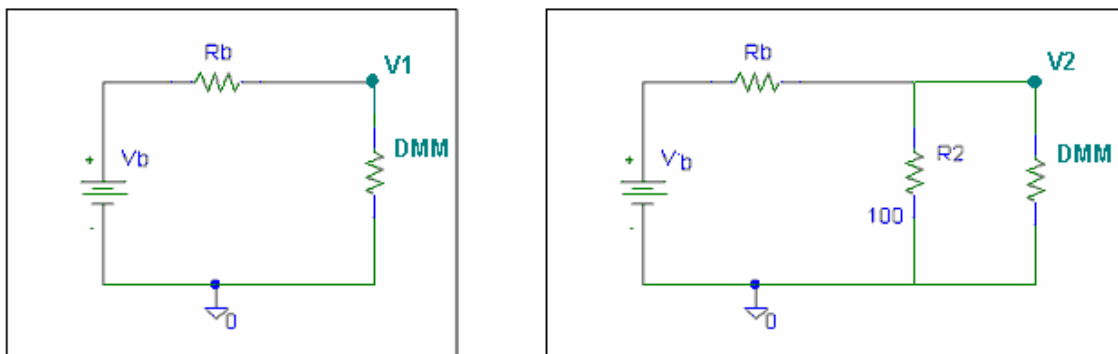


Figure 5 – Measuring the internal resistance of your battery

To find the characteristics of your battery, create the two circuits shown in figure 5, set up a voltage divider equation for each circuit, and use the known values in these circuits (100 ohm resistor and impedance of the DMM) to calculate R_b and V_b . Note that you should measure the actual resistance of the 100 ohm resistor to make your calculations as accurate as possible. Also, the internal impedance of the DMM is 10Meg ohms when measuring DC voltage. Caution: When you measure the output voltages of the second circuit, do not leave it connected for very long. Batteries discharge very quickly when they are attached to very small resistances. (The more you run down your battery, the slower your motor will turn.)

B-4. Initial Design Requirements

In order to satisfy the requirements for the basic design, a staff member must observe your motor spinning for at least 30 seconds. During this time, you should take a picture of the motor behavior and print it. Label the page "Basic Design", write the frequency on the printed sheet, and have the staff member, who observed the motor spinning, sign it. Include this page in appendix A-1 of your report. If the motor is particularly fast, post a copy (not the original) at the front of the room with your section number and names on it.

A second requirement for the basic design is measuring the exact voltage and resistance of your battery. Do not use the power supply for your initial design. Include these calculations in appendix A-2 of your report. You will also need to create an accurate circuit diagram and include it in appendix A-3 of your report.

Part C -- Building your Final Design

C-1. Improving your motor design

You have succeeded in creating a motor that spins. Now you need to make one that spins faster. There are many factors that go into this process.

a) Coil Design: If you maximize the inductance, you will make the coil spin faster. Consider the equation for the inductance of a ring-shaped coil. You will notice it depends upon the gauge of the wire, the core diameter, and the number of turns. How can you alter these from your original design to increase inductance? The basic Beakman design calls for a coil diameter to be equal to that of a toilet paper tube. Improved performance should be obtained if a smaller coil is built. How much smaller is hard to determine. Since the larger coil is known to work, reducing the diameter by about 25% or more should make things better without deviating too much from the basic design. You also have control over the type of wire you are using and the number of turns.

b) Coil Shape: Note that the coil need not be round. A rectangular or oval shaped coil may be faster. You can find an excellent site that describes the influence of coil shape on the inductance of a coil under "Inductance Calculations" on the links page for this course.

c) Proximity to Magnet: The closer the magnetic field of the coil is to the stationary magnets, the more power it will obtain from the magnet. Hence, a smaller diameter coil, with a lean design will spin faster.

d) Coil Weight: If the leads to your motor do not support its weight, it will not spin well. If the motor is too large and heavy, 1.5V will not provide enough power to make it spin fast. The speed of the motor also depends upon how well its leads are contacting the cradle. If the motor is heavier, then you will have good contact and the motor will spin faster. If the motor is lighter, it may not contact as well. This will slow down the speed, but you can fix this problem by adding springs. (This process is discussed in section C.2)

e) Coil Balance: A key issue noticed by nearly all motor builders is balance. The better balanced the coil, the faster it turns. If the coil is at all asymmetric from top to bottom, it will be out of balance and will not spin well. To achieve good balance, it has generally been found that a smaller coil will be more stable.

Thus, there is a tradeoff between wire gauge, number of turns, coil diameter, coil shape, coil weight, and balance that determines how fast an individual motor will spin. Getting a motor that spins well is somewhat of a trial and error process. You may find the Dr. Connor's Hints on the links page helpful in deciding how to redesign your motor.

For the final design, you do not need to use a battery. You can switch to the DC power supply set at 1.5V. Since batteries tend to run down over time, this will give you more consistent results. Do not use a voltage higher than 1.5V because a) it is forbidden by the ground rules and b) it will burn off your motor leads. Also, the stability of the cradle influences the speed of your motor. By moving the cradle to a stable surface, you will be able to obtain faster speeds. It is not recommended that you use your protoboard for this purpose because it may damage it.

For further information on what you can and cannot do when you redesign your motor, please see the ground rules in section C-3.

Try several motor designs. Once you have one you like that conforms to the Ground Rules described in section C-3, you will have to provide documented evidence that you have designed a motor (without springs) that turns for 30 seconds and at a faster rate than your initial design. You will include this data in appendix B of your report. (See requirements in section C-4 for details.)

C-2. Improving Contact with the Cradle

Having good contact between the coil leads and the cradle is essential to having a fast motor. You can test this by gently placing two hand-held (non-conducting) wires against the leads close to the cradle as your motor is spinning. If you press too hard, the motor will stop. However, if you press just hard enough to hold the leads against the cradle, the motor gets better contact and spins faster. In this class, we call the devices that hold the coil in the cradle "springs". In the above scenario, you have improved your motor using hand-held springs. You will need to provide documented evidence of a motor that spins

for at least 30 seconds when you use hand-held springs. Include this data in appendix C of your report. (See requirements in section C-4 for details.)

Your final design improvement will be to add mechanical (“hands-off”) springs to your design. You need to devise some system that successfully holds the coil leads gently against the cradle without creating so much friction that the motor stops. There are several popular methods for doing this. One is simply to hang a u-shaped piece of wire over each lead close to the place where it contacts the cradle. Another is to place one end of two wires into your motor support and rest the other end of each wire near the contact area. A third method is to close off each cradle with a piece of wire across the open end. The only stipulation for any of these methods is that the wires used as springs cannot become part of the circuit -- they cannot conduct electricity. Note that this motor must also conform to the ground rules in section C-3. You will need to provide documented evidence of a motor that spins for 30 seconds with mechanical springs and include this data in appendix D of your report. (See requirements in section C-4 for details.)

C-3. Ground Rules

Since this is somewhat of a competition to get the fastest motor, we need to establish some ground rules. The following is a list of what you can and cannot do in the final design:

YOU CAN:

1. Use a DC power supply in the studio set to no more than 1.5V or a single 1.5V battery. (You must use a battery for the initial design, Beakman’s motor in figure 1.)
2. Use the magnet wire provided by us in the studio.
3. Make your cradle from paper clips.
4. Change the shape of your coil as long as it still has an open end.
5. Use up to two of the magnets we provide in the studio.
6. Use a separate motor support to hold your motor and/or a battery holder.
7. Use non-conducting material to build your mechanical springs.
8. Use the wooden blocks to sand off the coating on the magnet wires.
9. Make your motors run for at least 30 seconds.

YOU CANNOT:

1. Use a voltage of greater than 1.5V from your power supply, more than one battery, or a battery rated at greater than 1.5 V.
2. Use magnet wire not provided by us.
3. Make your cradle from anything but the large paper clips we provide.
4. Make your cradle wire into a loop.
5. Use more than two magnets or use any magnets other than the ones provided.
6. Use creative sanding to create a double duty cycle.
7. Use springs made of material that is not somehow insulated from the circuit.
8. Sand the table tops or leave magnet wire on the floor.
(This damages the vacuum cleaners).
9. Get signed off on a motor that runs for less than 30 seconds.

Any design ideas that deviate significantly from the basic Beakman’s motor should be discussed with the instructor.

C-4. Final Design Requirements

In order to satisfy the requirements for the final design you must have a staff member observe three situations: a motor operating with no springs, a motor operating hand-held springs, and a motor operating with mechanical springs. These observation can all be made using the same motor, provided it is not the initial Beakman’s motor from part A. If you prefer, you can use a different motor for any of these situations. For each situation, have a staff member observe your motor spinning for at least 30 seconds. During this time, you should take a picture of the motor behavior and print it. Label the page, write the frequency on the printed sheet, and have the staff member who observed the motor spinning, sign it. If the motor is particularly fast, post a copy (not the original) at the front of the room with your section number and names on it.

Include the output from the final motor design without springs in appendix B-1 of your report. You also need to create a new circuit diagram with the component values for the new motor. Include this in appendix B-2 of your report. Don’t forget to measure any other components in the circuit that have been added or changed. Appendix C of your report should contain the output from your motor using hand-held springs and Appendix D of your report should contain the output from your motor with mechanical springs. If you choose to use a different motor for either of these cases, include an appropriate circuit diagram.

Part D – Comparing the Motors

Once you have built your motors, you need to demonstrate that you have actually improved on the original design. Fill in the following chart and include it in the conclusion of your report. If you have more motors to compare, you can modify it to include the additional motor descriptions and data.

	speed (Hz)	% improvement over Beakman’s	% improvement over previous design
Beakman’s Motor		XXX	XXX
Motor without springs			
Motor with springs			

To find the percent improvement, use the following equation:

$$\% \text{ improvement} = \frac{\text{newspeed} - \text{originalspeed}}{\text{originalspeed}} \times 100\%$$

Part E -- Your Report

For this project we ask that you follow the outlines in the appendices of this handout when writing up your report. You will find that the organization of the report will be quite rigid. We find that, if all the reports are consistent, it takes less time to get them graded and returned to you. It also ensures that you are graded on what you know and how well you did the work, rather than on whether you remembered to include certain pieces of information (or did an effective job of hiding the fact that you did not). You will be penalized if you deviate from this format.

Appendix I of this handout contains a list of tasks you must complete in order to satisfy the requirements of the project. These are tasks that, for the most part, must be done in class. Appendix II of this handout contains a detailed explanation of what the appendices of your report should include. Appendix III of this handout describes the report itself and asks some questions you will be expected to answer.

Part F -- Extra Credit Opportunities

Creativity (0-10 pt)

Exceptionally creative approaches to implementation or in the final design.

Excessive speed (0-10 pt)

If your motor is one of the fastest in the section, you will be eligible for an additional point.

Experimentation and comparison (0-10 pt)

Engineering problems are often solved by experimenting with different types of configurations, finding the changes that have the most positive effects, and systematically choosing a course of action based on those experiments. There are many variables to explore including wire gauge, number of turns, shape and size of armature, how leads are sanded, placement of magnets, mass of armature, battery type, type of spring design, balance of coil, etc.

Appendix I: Task List

- A. Build the basic Beakman's motor.
1. Demonstrate that it works for at least 30 seconds.
 2. Take data that verifies the frequency of your motor.
* mark frequency and get signature
 3. Determine the actual voltage and resistance of your battery.
 4. Take measurements of the other components in your circuit.
- B. Improve your motor design to get faster speeds.
1. Demonstrate that a design works for at least 30 seconds (no springs).
 2. Take data that verifies the frequency of your motor.
* mark frequency and get signature
 3. Take measurements of any components in your circuit not used in the initial design.
 4. Optional: Take data for any other motors you tested successfully without springs.
* mark frequency
- C. Improve contact between motor coil and paper clips using hand-held springs.
1. Demonstrate that a design works for at least 30 seconds using hand-held springs.
 2. Take data that verifies the frequency of your motor.
* mark frequency and get signature
 3. Take measurements of any components in your circuit not used in another design.
 4. Optional: Take data for any other motors you tested successfully using hand-held springs.
* mark frequency
- D. Build mechanical springs to use instead of your hands.
1. Demonstrate that a design works for at least 30 seconds your mechanical springs.
 2. Take data that verifies the frequency of your motor.
* mark frequency and get signature
 3. Take measurements of any components in your circuit not used in another design.
 4. Optional: Take data for any other motors you tested successfully using mechanical springs.
- E. Assemble the appendix (as described in appendix II of this handout).
- F. Write your group report (as described in appendix III of this handout).

Appendix II: The Appendix of Your Report

The following list of items must be included in the appendix of your report, numbered and ordered as listed. This will help make sure that everyone includes everything that is required. In your report you should refer to each appendix specifically as needed to help illustrate your descriptions and conclusions. If you would like, you can include a second copy of what is in the appendix in order to better illustrate what you are trying to say, however, this is not necessary and cannot be used as a replacement for the contents of the appendix.

Appendix A: Basic Beakman's Motor

1. Agilent Plot of motor speed
 - * plot title
 - * frequency (cycles/sec) clearly indicated
 - * signature.
2. Battery Calculations (2 equations in two unknowns)
3. Circuit Diagram including
 - * title
 - * voltage and resistance of your battery from appendix A2
 - * actual inductance and resistance of your motor coil
 - * additional resistances (such as paper clips) clearly identified
 - * the measuring device (and its impedance)
 - * switch representing the commutator
4. Additional plots taken of this motor. (This appendix may be blank.)
 - * a title for each plot
 - * frequency clearly indicated
 - * no signature required on these plots

Appendix B: Motor without Springs

1. Agilent plot of motor speed
 - * plot title
 - * frequency (cycles/sec) clearly indicated
 - * signature
2. Circuit Diagram including
 - * title
 - * actual voltage provided by power supply
 - * actual inductance and resistance of your motor coil
 - * additional resistances (such as paper clips) clearly identified
 - * the measuring device (and its impedance)
 - * switch representing commutator
3. Additional plots of this motor, or others without springs.
(This appendix may be blank.)
 - * a title for each plot
 - * frequency clearly indicated
 - * no signature required on these plots

Appendix III: Your Group Report (80 points)Introduction (5 pts)

- * State the purpose of the project.
- * Also include at least 2 topics you studied in this course that helped you understand the project.

Theory (10 pts)

- * Describe the basic theory. What are the forces that enable the motor to spin? Where do they come from? How and when do they interact?
- * Describe what happens to the voltage across the coil as the motor spins. (A sketch of the circuit when the coil is connected and not connected will help to illustrate this.)
- * Use your own words and be sure to cite any resources you used in appendix E.
- * Demonstrate to the grader that you understand what is happening.

Initial Design (12 pts)

1. Describe your initial design.
 - * How did you build it?
 - * What did you learn about designing a motor when you were trying to get your initial design to spin?
 - * What results did you get for the voltage and resistance of the battery?
 - * Include a reference to where the circuit diagram is located in the appendices.
2. Describe your initial results.
 - * How well did your motor work?
 - * What was the frequency in cycles/second?
What is this in rpm (rotations per minute)?
 - * Include a reference to where the signed output is located in the appendices.

Final Design without springs (12 pts)

1. Describe your final design without springs.
 - * What criteria did you use to redesign your motor for faster speeds?
 - * What did your final motor look like? (Turns, wire gauge, shape, etc.)
 - * What did you learn about designing a motor when you were trying to get your final design it to spin faster?
 - * Include a reference to where the circuit diagram is located in the appendices.
2. Describe your final results without springs.
 - * How much better does this motor work than the initial design?
 - * What was the frequency in cycles/second?
What is this in rpm (rotations per minute)?
 - * Include a reference to where the signed output is located in the appendices.

Final Design with springs (16 pts)

1. Describe your spring design.
 - * What did you learn about designing a spring when you used your hand-held springs?
 - * What criteria did you use to design the mechanical springs?

- * What did you learn about motor design when you were trying to get your motor to work well with mechanical springs?
 - * Include a reference to where the circuit diagram (if different) is located in the appendices.
2. Describe your final results with springs.
- * Did the motor work better with springs?
 - * How close to using your hands were you able to get with mechanical springs? (Sometimes the mechanical springs, if well designed, will give a faster motor.)
 - * What was the frequency of your motor in both cases in cycles/second? What is this in rpm (rotations per minute)?
 - * Include a reference to where your signed output (with hand-held and mechanical springs) is located in the appendices.

Conclusions (8 pts)

In this part, we want a summary of the basic conclusions you can draw from the project. Include the following chart comparing the speeds of the four different motors you have tested. By what percentage were you able to improve the motor speed with each design change? Why were the fast ones faster? Why did the design changes you made make this happen? Which factors seemed to make the most difference? What could you do in the future to improve the design even more? Discuss any extra credit activities you did and why.

Personal Responsibilities (4 pts)

- * How were the tasks divided between group members?

Appendices (3 pts)

- * See appendix II of this handout

Extra Credit (0-10 pts)

- * Include any details that you would like to include about anything you tried above and beyond the basics of the project.

Your grade will also include a general assessment of project understanding and quality worth up to 10 points. You do not need to write a general assessment.

Total: 70 points for project report
+ 10 points for general assessment of report
+ 20 points for attendance
= 100 points

Attendance (20 possible points)

3 classes (20 points) 2 classes (10 points) 1 class (0 points)

Minus 5 points for each late.

No attendance at all = No grade for project.