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Report
On
The Shakesmograph Seismometer

I. Introduction

Rho Engineering Group is pleased to be part of your project and has created the "Shakesmograph" seismology unit, a complex system made up of four separate subsystems. This report will explain each of the parts and their functions on a level that is easy to understand. Our hope is that you will thoroughly understand all aspects of the Shakesmograph upon reading this report.

You set certain requirements at the beginning of this term, and the Shakesmograph goes above and beyond these requirements. First, it has been built from scratch with common materials, and the total cost is under the budget of $150. The seismometer can detect earthquakes of magnitude 6 or higher, it has the ability to record a period of up to twenty seconds, and our highly sensitive magnets and the coil enable earthquakes of smaller magnitude to be recorded as well. Most important, the seismometer detects earthquakes from any location and can be easily assembled by a person with limited mechanical skills. The final design hooks up to the filter and amplifier you provided, and the data collected is transmitted to a computer through a $100 DI-154RS analog-digital converter instead of the earlier method of transcribing the information onto a sheet of paper.

At the start of the project, there were several basic seismometer configurations to choose from. An inertial seismometer measures seismic waves by outputting a signal that is relative to the motion between a frame usually attached to the ground and an internal reference mass (an oscillator in either a spring-mass or a pendulum-type configuration). The strain seismometer records the magnitude of the seismic waves by generating an output proportional to the distance between two points.

We also researched different types of working seismometers for design ideas, and a few caught our attention. The Lehman design has a swinging pendulum with a set of magnets and a pickup coil on the pendulum. One set of magnets is at the end of the pendulum for damping, and a magnet with a pickup coil within the last two-thirds of the pendulum register the data. This is the basic idea for the operation of the transducer.

A similar design is the Force-Balance seismometer. This machine operates in the same fashion as the Lehman design by swinging on a pendulum, but the pickup coil and magnets (LVDT) are arranged very differently using a feedback loop for a more accurate reading. The other options we considered involve the disturbance of light or sound waves to measure ground movement, but issues such as cost prevented us from using these configurations.

We planned short-term goals in order to stay on task and avoid digression. The project was planned as follows:

1. Research background information on seismology
2. Come up with at least 3 possible designs (Lehman, force-balance, sound and/or light)
3. Further our research on possible designs
4. Test and improve based on results obtained
5. Build prototype (client’s equipment, self-bought materials, fulfill client’s requirements)
6. Write final report and present to client

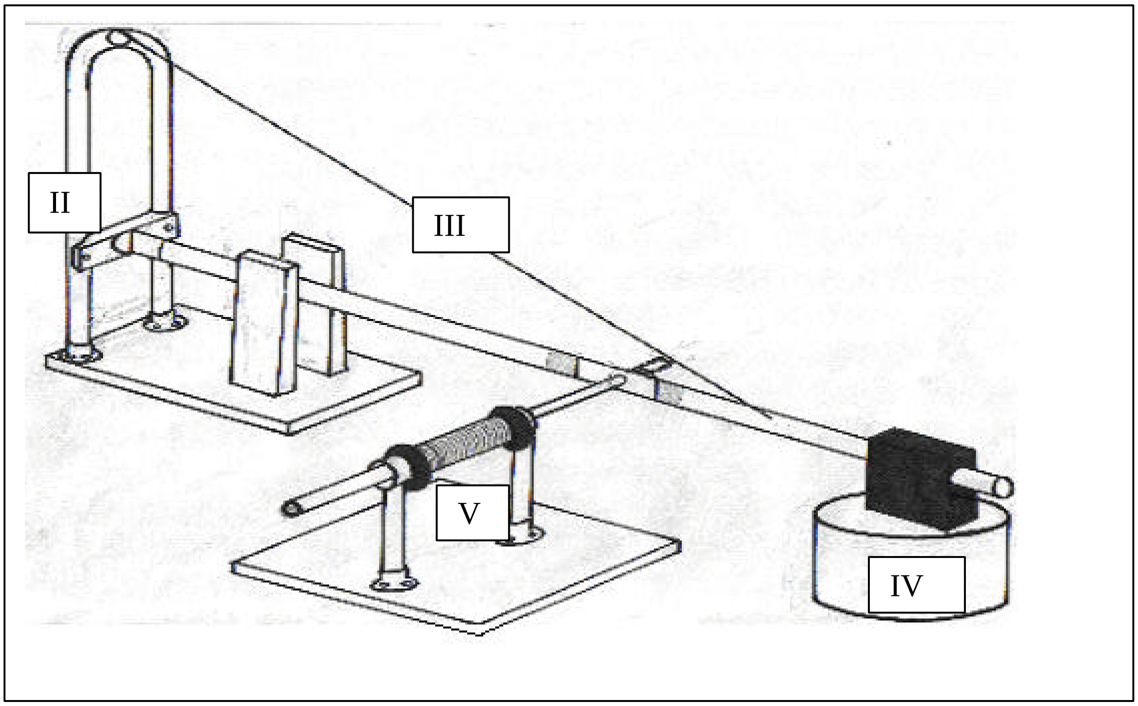


Figure 1.1

Overview of the Shakesmograph Design

Throughout this process, we purposely kept you updated on our progress with memos and presentations. When we began research of the mechanics of design, we began to organize a portfolio containing the details and drawings of our design. This portfolio contains every possible graphic of our design and its assembly. The portfolio is meant to be a visual supplement to this written report. Once again we hope that this report and graphics portfolio will help you comprehend the potential of our design, the Shakesmograph seismometer. For a better understanding, see Figure 1.1.

II. Base and Frame

The first subsystem consists of the support base and frame. Since we have chosen the Lehman seismometer as the foundation of the Shakesmograph, the first subsystem does not have any significant change from the Lehman design. The Lehman seismometer consists of a weighted horizontal rod known as a pendulum that is allowed to pivot near the bottom of a frame at one end. The other end is suspended to the top of the frame by a wire or guitar string [1]. The base and support hold the pendulum and allow it to stand horizontally. Additionally, the top of the frame is used to hold the wire or string at an angle with the pendulum. The pendulum is one of the main components of the seismometer because it has to swing and respond to the seismic waves during an earthquake. Therefore, the pendulum requires a support that is the frame and the base.

a. ***Technical Criteria***

The materials can be chosen, according to one's budget, from diverse materials such as aluminum or wood. In this case to meet the client's requirements, we developed a decision matrix and estimated costs to get the best materials for our design. We developed two matrices to decide the material for the frame and the base (see Tables 1 and 2).

Table 1. Decision Matrix (Base)

Materials	**Cost**	**Convenience**	**Durability**	**Total**
Stone	2	2	4	8
Aluminum	3	2	4	9
Wood	5	4	2	11
			Range 1-5	**5 is best**

Looking for convenience and low cost we found out that for the base the best material would be wood. When we researched possible materials, stone was the most expensive since it is difficult to shape, aluminum was also somewhat expensive since it is a light, durable material, and wood was the cheapest because the main labor cost is cutting down the tree from which it comes from and transporting it to the lumber factory. Also, wood is most convenient to use since screws can be drilled into it in order to attach it to other pieces of wood or low-resistant material.

Table 2. Decision Matrix (Frame)

Materials	**Cost**	**Convenience**	**Durability**	**Total**
Plastic pipes	4	1	5	10
Iron pipes	2	4	6	12
Aluminum Bars	1	4	5	10
			Ranging 1-5	**5 is best**

For the frame, the material we chose was a metal pipe used in plumbing. Aluminum bars are expensive because they are very light and efficient, and plastic pipes are cheap but not quite as strong. Therefore, we chose iron pipes that are durable because they are made of metal, and they run cheap since iron is not very light or easy to work with. Although iron is not as popular as aluminum in modern construction, it is convenient for our purposes of a sturdy, low-cost frame.

b. ***Assembly and Operation***

The construction of the base and frame is not difficult. The following is a detailed explanation of how to construct it. First, the measurements for the base and frame should be proportional to the pendulum. The frame is made up of plumbing pipes with a diameter of 5 cm each. [2]. The pipe's height is approximately 46 cm and two of them are needed. The upper crosspiece uses the same diameter as the pipe and is 10 cm long. The frame and the upper crosspiece are joined together using 1.5 cm diameter elbows (90° elbows), (see Figure 2.1 & 2.2). Drill a hole that has a diameter of 1.5 cm in the center of the upper crosspiece, and put a bolt with the same diameter into the drilled hole. After a wire is attached from the bolt to the pendulum, it should form an angle of about 30 to 40°. The lower crosspiece is a plastic pipe with a diameter of 1.25 cm that is placed 9 cm above the ground and 7 cm above the base between the two upright pipes. Drill holes in the wood base to attach the entire frame using nuts and bolts. In the center of the lower crosspiece, a machine bolt screws into the plastic pipe from back to front and connects a metal L-bracket to the pipe in order for the pendulum to rest upon. The L-bracket acts as the bearing plate for the knife-edge at the pivot end of the pendulum [3]. Finally, the base is made of wood and its dimensions are 40 x 25 x 2 cm thick. The base has two stops to control the pendulum; they are each 9 cm high and 1.5 cm thick. [4]

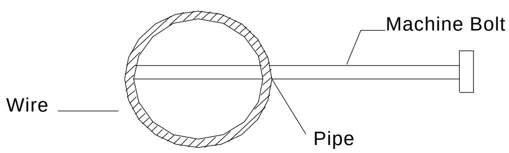


Figure 2.2 Frame centerpiece

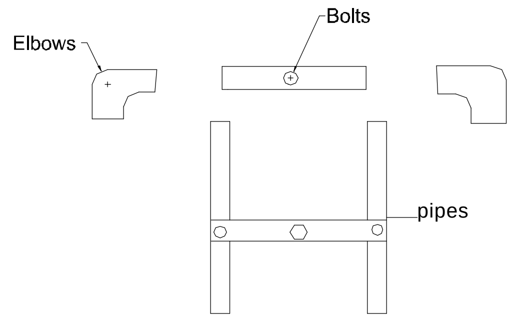


Figure 2.1 Parts of frame

Table 3. Estimated Costs*

Project: Shakesmograph (Subsystem 1)	**Author: Livia J. Sivila**		
Material Description	**Amount**	**Cost**	
		Unit	**Total**
Pipe (2 cm)	1	$ 1.00	$ 1.00
Nuts & bolts (1.5cm)	5	$ 0.65	$ 3.25
Wood Base	1	$ 8.00	$ 8.00
Machine nuts	4	$ 0.75	$ 3.20
Elbows (1.5 cm)	2	$ 1.00	$ 2.00
			$17.25

*The prices are approximate and they may change for mass production [5], [6], and [7].

III. String

a. Assembly and Function

The purpose of the guitar string is to securely support and stabilize the Shakesmograph's pendulum [1]. The light string is about 0.56 mm in diameter and 76.2 cm in length (see Figure 3.1) [3]. We will use the lowest, thickest E-string from a guitar. Using the thickest string allows for more support for the pendulum and prevents it from bouncing out of control [2]. The string will be connected to the frame by a peg-like screw (see Figures 3.2 and 3.3) and tied to the pendulum manually through a hole (See Figure 3.4).

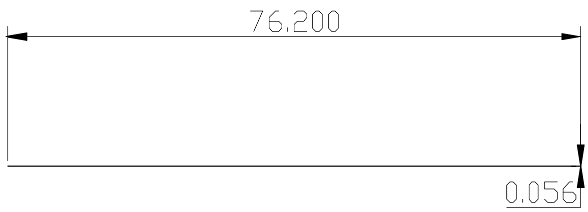


Figure 1: Guitar String Close-Up
*All dimensions in cm.

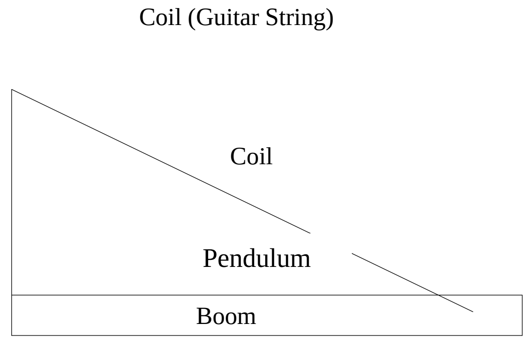


Figure 2: Coil Subsystem

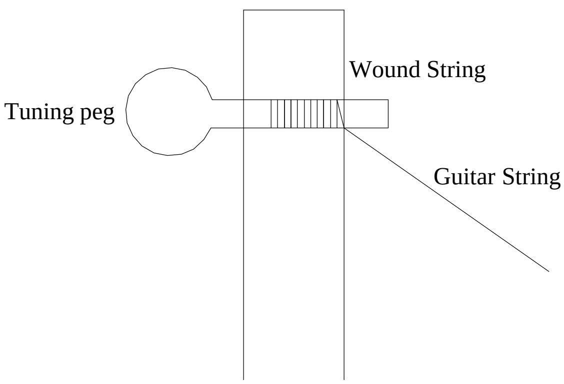


Figure 3: String Connection 1

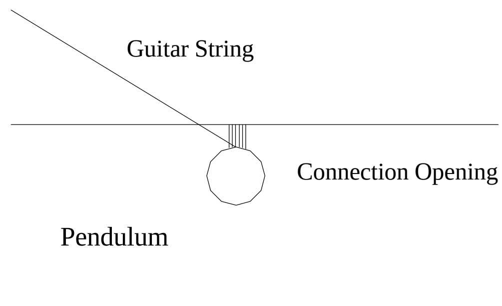


Figure 4: String Connection 2

b. Meeting Requirements

The seismometer coil will successfully meet the client requirements. Sold at a store-bought price of $0.59 and a mass-produced price of $0.35, the Shakesmograph's light guitar string will be the least expensive part of the seismometer. Along with a reasonable cost, the string is also child environment-friendly. We will reach a safety status by attaching a low E-string secure enough for both efficiency and safety. In this case, the string is less likely to dangerously snap because it is a thick string. In order to ensure ultimate safety, we will apply a safety warning stating: Do not touch the string. This system is also friendly toward the environment; it will not give off any chemicals and will not rust. Along with these attributes, the guitar string in the string subsystem is the most cost-efficient and performance-enhancing option compared to a chain. Even though a chain can offer more support, it will give the same results with regards to accuracy. In this particular case, we chose the less expensive route.

IV. Pendulum and Damping Unit

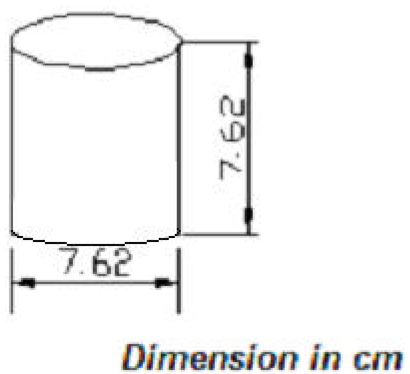
The knife-edge pendulum is made of plastic pipe that can be found in any Home Depot store. At the end of this pendulum will be a wooden knife-edge, and it will be attached onto the centerpiece of the frame with the support of the string. About ¾ out from the knife-edge, there will be a joint sticking out from the pendulum to hold the pipe that the lacquer coil is wound around. The coil will be attached to the right of the instrument. The oil damping system will be placed at the end of the pendulum with a flag dipped inside a can of oil.

a. Assembly and Operation

The purpose of the damping mechanism is to eliminate the resonance of the pendulum so that the instrument can respond to a broad range of periods. Building the oil damping system is not as easy as it may sound. It requires many trial and errors to adjust the period and try to get it to fall within the range of at least 20 seconds. To begin, make sure the damping oil container is empty and place it underneath the end of the pendulum (See Figure 4.2 for the dimensions of the oilcan). Second, screw the aluminum flag to the end of the pendulum and place it well inside the oilcan, but not in contact with either the bottom of the container or its walls (see Figure 4.3). The clearance is adequate if the pendulum can freely move at least 1.5 cm in each direction from its resting point.

b. Meeting Requirements

According to the requirements memo, the sensor can be based on the voltage generated by relative motion between a coil and magnet and should cost below $150 [8]. The design for the magnets, lacquer coil, and the plastic pipe completely complies with these standards because it is a type of coil and magnet transducer, which means it is cost efficient. Also, the damping system will register a 20 second period, which is a requirement you specified. Other than these specific instructions, there aren't any conflicts with industry standards or safety and environmental criteria.



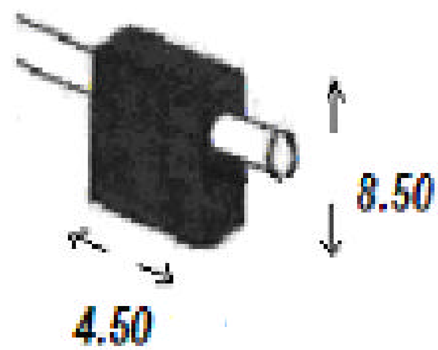


Figure 4.2 Oilcan

Dimensions in cm

Figure 4.3 Flag

To calibrate the oil damping system, gently push the pendulum and note its period of oscillation. By tweaking the pendulum and adjusting the screw behind the spring, we can get a period of up to around 14 seconds, but keep in mind that this is without the oil inside the container. Once the adjustment is complete, fill the container up to the brim with oil. After negotiating with an expert in the auto industry, the preferred oil to be used in this situation is 10W-30 oil [9]. This oil will not freeze at extreme temperature and its viscosity will remain constant so that the flag can move with a fixed resistance (See Figure 4.4 for the overall picture of the oil damping system).

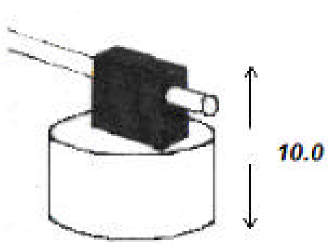


Figure 4.4 Flag with oilcan

Dimensions in cm

c. Pendulum

The pendulum is approximately 75 cm long and made out of wood. The knife-edge will be mounted onto the centerpiece of the base and will be supported by the guitar string. About ¾ out from the knife-edge, there will be a coil attached to the end of the pendulum to serve as the pickup unit for the signal produced by the magnets. The oil damping system is located at the end of the pendulum. See Figure 4.5 for a complete view of the knife-edge pendulum.

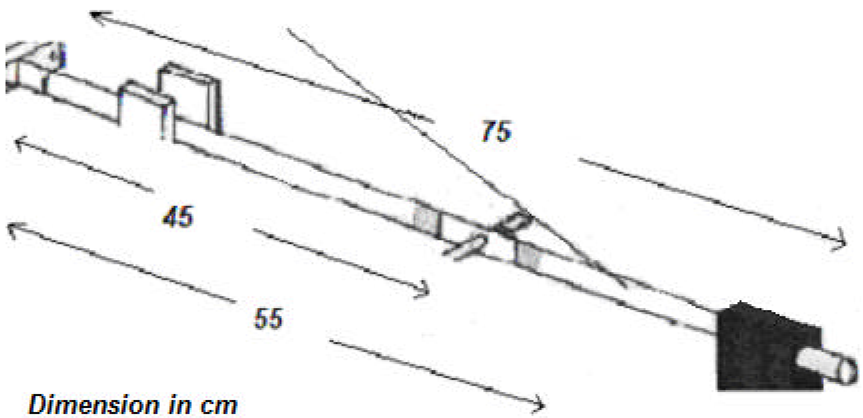


Figure 4.5 Pendulum and damping unit

The plastic pipe and joint screw together to form one piece. Then, the joint will be hooked up to the lacquer coil of the transducer, so the piece of steel parallels the ground and forms a right angle with the pendulum.

V. Magnet and Coil Transducer

The magnet and coil is the subsystem that senses the movement of the Earth and outputs a proportional magnetic signal. The steel core of the magnet and coil transducer is connected by wedging it into a hole in the pendulum and has a strong magnet on the end that magnetizes the entire piece of steel. The pendulum is the piece that makes it possible for the core to remain completely separate from the rest the coil, which is essential in order to eliminate friction between the steel core and the outer coil. A string extends from the top of the support to the end of the pendulum, which suspends the entire pendulum and the steel core above ground. The suspension is also essential for the oil-damping unit, which contains a core that cannot be in contact with the metal container. Without the physical connection of the steel core to the pendulum, earthquakes would not be recorded. The pendulum's pivot point enables it to oscillate in an earthquake, setting the magnetized steel core into motion and producing a magnetic field. The analog-digital converter then records this signal. The motion from an earthquake begins at the pivot point of the pendulum, and is then converted from mechanical energy into magnetic energy by the magnet and coil transducer.

The coil is offset to one side of the pendulum. As shown in Figure 5.1, the steel core is directly connected to the pendulum, which enables movement of the core that is equivalent to the movement of the pendulum during an earthquake. Figure 5.2 contains the dimensions of the subsystem. This entire subsystem is approximately 15 cm long with a 13 cm by 11 cm base supporting it. The base suspends the bobbin, a hollow tube that separates the steel core from the coil, above the ground. The exact center of the bobbin must be 23 cm high and 15 cm long with a 6 cm diameter. The steel core must have a diameter of 2.54 cm to ensure that there will be enough space so that no contact will exist between the core and the bobbin. The coil consists of a ductile, lacquered wire wrapped around the length of the pipe between the bobbins [10]. The magnetic signal is created from the movement of the magnetized steel core throughout the hollow bobbin. Since the movement of the magnetic steel core between the wire coils creates a magnetic field, a current is generated. The magnetized steel core, bobbin, coil, and support stand are the four components that make up this subsystem. Together, the components convert the mechanical energy generated by an earthquake into a magnetic signal that can be easily recorded.

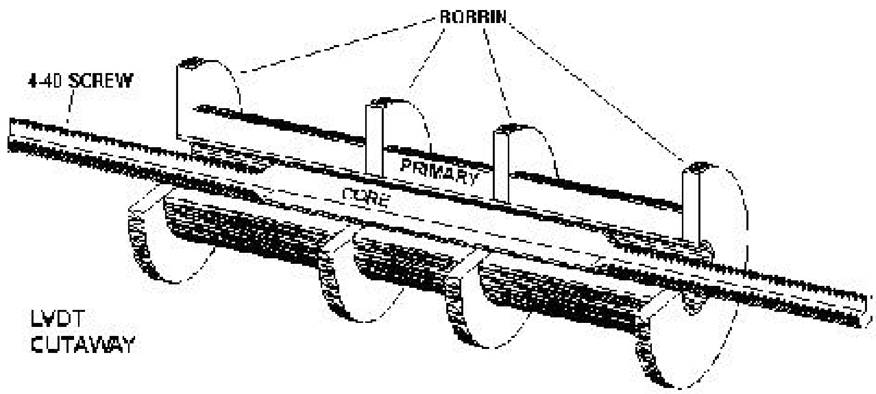


Figure 5.1 Overview of magnet and coil

The magnet and coil transducer contribute to the requirement of the system as a whole [11]. With this component, the seismometer will not only be able to detect earthquakes of magnitude 7 or above, earthquakes of lower magnitude may be detected due to the frictionless system of the steel passing through the coil [12]. Although this subsystem is more expensive than the rest, its cost is lower than twenty dollars, which leaves more than enough funding for the other, cheaper subsystems [8].

a. Technical Specifications

The materials used in this subsystem are critical to whether or not the design will function. The bobbin of the transducer is made of plastic because it is a non-magnetic material and will not interfere in the magnetic field produced by the steel. The coil around the bobbin is made from lacquered wire [8] in order to generate a non-interfering current. When first contemplating the design, we thought it would be useful to construct a primary and secondary coil [12], but then we later found that only one set of wires can hook up to the amplifier, and therefore, secondary coils would have complicated the system [13]. The base and legs that support the bobbin are constructed from wood because it is a cheap, durable material.

Table 5.1

Dimensions of Magnet and Coil Transducer

Part of Transducer	**Size (cm)**
Diameter of Inner Tube	3.0
Diameter of Outer Tube	3.6
Diameter of Bobbin Protrusion	6.1
Diameter of Legs	1.0
Length of LVDT	12.7
Length of Legs	9.0
Length of Base	20.0
Width of Base	10.2
Length of Steel Rod	17.8
Diameter of Steel Rod	2.5

The following is an orthographic drawing of the coil component and a drawing of the steel rod.

Figure 5.2 Coil Component

Figure 5.3 Steel Rod

This subsystem only operates when movement occurs in the pendulum and causes the steel rod to move. The Shakesmograph is a pendulum design that is similar to the Lehman design and will move from side to side rather than up and down [14]. Therefore, it will detect surface waves. Since the steel rod is attached at a right angle and parallel with the ground, it will run directly through the center of the bobbin and cause a signal to be sent to the amplifier through the lacquered wire. Since the coil and steel rod aren't in physical contact, it provides a friction free movement and is appropriate for applications with a very high number of cycles [12].

b. Assembly and Operation

The transducer is assembled by first constructing the bobbin to the correct dimensions. After the bobbin is modified, the lacquered wire is wrapped around the bobbin in a very orderly and precise fashion for about 1000 turns. When the lacquered wire is wrapped 1000 turns, the coil has an amplification of 1 micrometer. This is true because of Faraday's law. It states that: $V = -N (\Delta\phi/\Delta t)$, where N = number of turns, ϕ = magnetic flux, and t = time [15]. Once the actual coil component is built, the legs need to be constructed from wood to fit onto the outside 1.75 cm of the bobbin; the legs are then placed onto the base platform, also made of wood. Next, the steel rod will be wedged into the pendulum so that the piece of steel almost parallels the ground and forms a 90-degree angle with the pendulum. Last, the magnetized steel rod will need to be positioned correctly because it needs to run through the center of the bobbin without any physical contact (see Figure 5.4).

Figure 5.4 Complete View of Transducer

c. Meeting Requirements

According to the Requirements Memo, the sensor can be based on the voltage generated by relative motion between a coil and magnet and should be under $150 [8]. Our design for the transducer complies with these standards because it is a type of coil and magnet transducer, which means it is cost efficient because no outside power source is necessary. The transducer also contributes to the industrial, environmental, and safety standards of the system. It has been in use for several years, and has proven to be one of the most accurate methods of detecting motion. The only output is a magnetic current, which won't harm the environment, and the users will be safe as well because the current generated is not strong enough to inflict injury.

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VI. Conclusion

During the construction process, we had to change some components of the original Shakesmograph design. The frame is not completely made out of metal; we used plastic pipes to connect the vertical metal rods. The hinge unit on the beginning of the pendulum does not utilize a metal knife-edge; we used a sharp wooden edge that rests upon a metal L-bracket. The most significant change in the design was our transducer (magnets and coil). We chose to use a lacquered coil wrapped around a plastic tube with magnets positioned on the outside to generate a magnetic field. This unit proved to be much simpler to construct.

The Shakesmograph seismometer will be a useful learning tool for students across the nation. The essential components are cheap and easy to construct. The total cost of the parts excluding the amplifier, filter, and A-D converter was under $25 (See Table 6.1). The construction of the entire system is simple, and someone with few technical and mechanical skills will be able to assemble it. Any school with “spare change” in their budget will be able to purchase a Shakesmograph unit.

Table 6.1 Cost summary of Shakesmograph

Materials	Cost
PCV Pipe	4.50
Lacquered Wire	5.00
Steel Rod	3.50
Legs & Base	1.30
Magnets	1.30
Metal supports	3.00
Wooden base	1.00
Flag	.50
Oil & Can	2.50
Construction Labor	5.00
String	.35
Screws	.50
Total	$ 28.45

The system consists of the frame and base, string, magnet and coil, and damping unit connected to the end of the pendulum. The frame and base are connected and provide the main support of the system. The pendulum meets the frame at a wooden knife-edge, and runs parallel to the ground with the support of the string that connects the top of the frame to the far end of the pendulum. The flag of the damping unit is connected at the end of the pendulum as well and suspended in a can of 10W-30 oil. The steel bar is offset 90 degrees to the right of the pendulum at about ¾ the total distance. The steel bar is magnetized so that it can produce a magnetic field when it moves through the lacquered coils. These coils are wrapped around a plastic pipe with a plastic bobbin at each end in order to ensure frictionless motion between the steel bar and the coil.

We hope that this report has helped you to comprehend the potential of our design. The Shakesmograph seismometer can be a useful educational tool for all students if schools were to purchase this unit at our reasonable price. With your help, our design could improve a vast majority of young students' knowledge of seismology. Please feel free to continue our communication regarding this design by email: dagonzal@mines.edu, or by phone: (303) 215-6210. Thank you for your business.

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