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Detecting Micron-Size Movements

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Abstract

The heartbeat of a cockroach was detected using an electronic circuit. This was performed using a Hall effect transducer and a magnet fragment attached to the insect. Various amplifiers and potentiometers were used to clean up the signal and make it readable by an analog-to-digital converter. As well, the final signal was filtered to eliminate the noise band produced initially.

It was determined that the average heartbeat of the cockroach was 4-5 beats every ten seconds. This was slowed down to 2 beats every ten seconds by subjecting the insect to the temperature of a refrigerator for 15 minutes. This rate was also increased by subjecting the insect to stressful situations such as human touch.

The method of detection was seen to rely on the distance the sensor was from the magnet. No adjustments to the circuit components were made once it was initially assembled.

1 Introduction

There's a lot going on down among the microns. What we perceive as a rigid surface squashes easily under a finger's gentle pressure if we could somehow view it from a distance of a millionth of a meter.

Biological processes reshape many living things on this scale. For example, every beat of an insect's dorsal vessel – essentially its heart – flexes its abdomen by a few microns.

Such micrometer changes in distance can be detected by affixing miniscule magnets to moving objects and relying on a special sensor to pick up the variation in the magnetic field caused by the shifting magnet. The sensitivity of such a setup depends on the fact that all magnets are dipolar. These poles would cancel each other perfectly if they were not separated by the length of the magnet. This self-cancellation quality makes the strength of a magnetic field fall quite fast over space. Tripling the range to a magnet weakens the field by a factor of 27 (the cube of the distance). The size of the magnet sets the scale by which this fall-off can be quantified. Hence the closer together the magnetic poles are (that is, the smaller the magnet), the more rapidly the magnetic field changes over distance. That, in turn produces a larger signal for a micron-size shift.

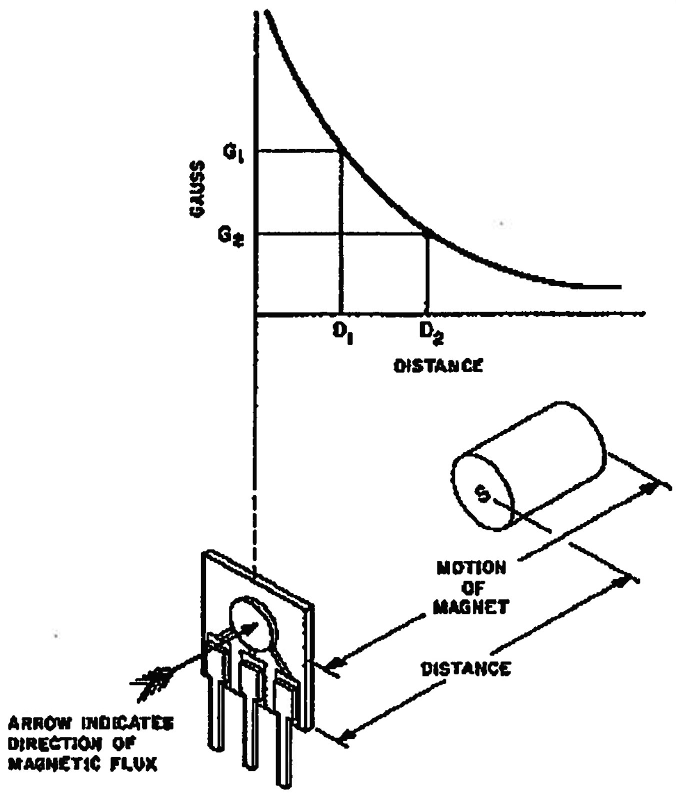
The beauty of performing an experiment such as this is that it allows the complete tying together of *all* of the concepts learned in this course. It will be seen in this lab report that offset voltages, amplification, noise reduction and analog-to-digital conversion had to be accounted for. These were, in *exactly* the same order, the concepts learned throughout the duration of this course. Hence this experiment provides the student with a complete $wrap - up$ to the course.

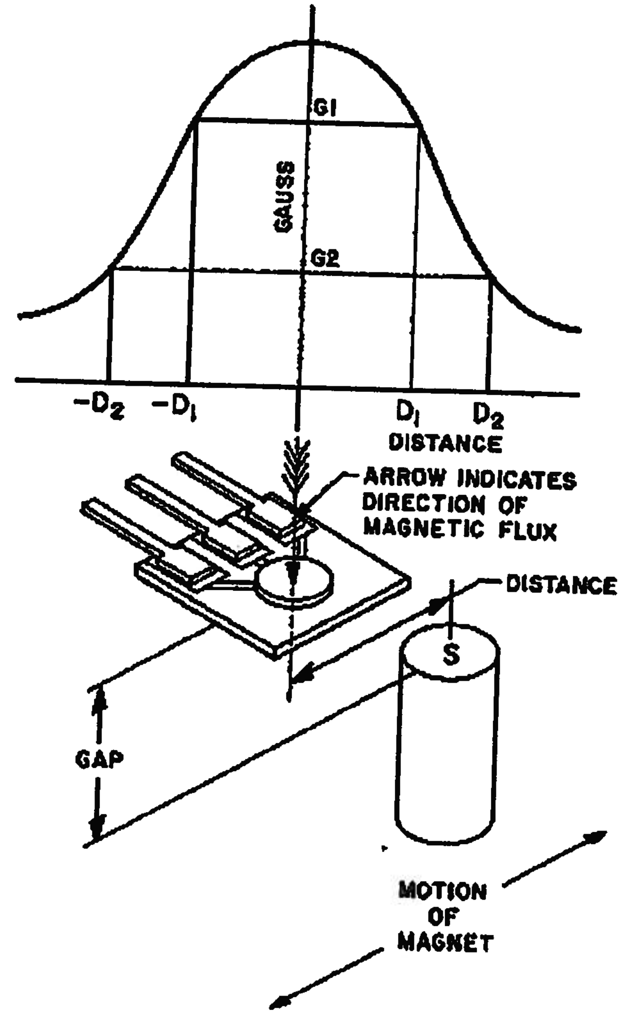
2 Theory

2.1 The Sensor

The detection of voltage signals in this experiment was performed using a Hall effect transducer (HET). These sensors are very small, light, extremely sensitive and easy to use. Furthermore, the theory of how the sensors work is no more difficult to understand than the simple theory behind the Hall effect. One can think of the sensor as being filled with evenly distributed electrons. Therefore, no potential difference across the chip can be measured. When in the presence of a magnetic field however, the electrons shift towards one side of the chip and a potential difference can be measured. The potential difference across the chip is amplified by an operational amplifier incorporated in the product. Typically, HETs change their output 25 millivolts for each one-gauss shift in the magnetic field [5]. For this experiment, chip model SS94A1F was used.

In using such sensors, the corresponding magnet can be very minute, provided that the magnetic field orientation is controlled. In this experiment, a rare-earth magnet was shattered and only a single *crumb* was used. But to understand the full theory of detection using HETs, one must consider the broader scope of what experimental setups generate what final *gauss (or also voltage) vs. distance* curves. Consider the following page of different configurations to gain some idea of the potential such detection methods have for other experiments. Nothing further will be commented on in regards to this. It is left up to the reader's imagination to come up with other interesting experimental applications.





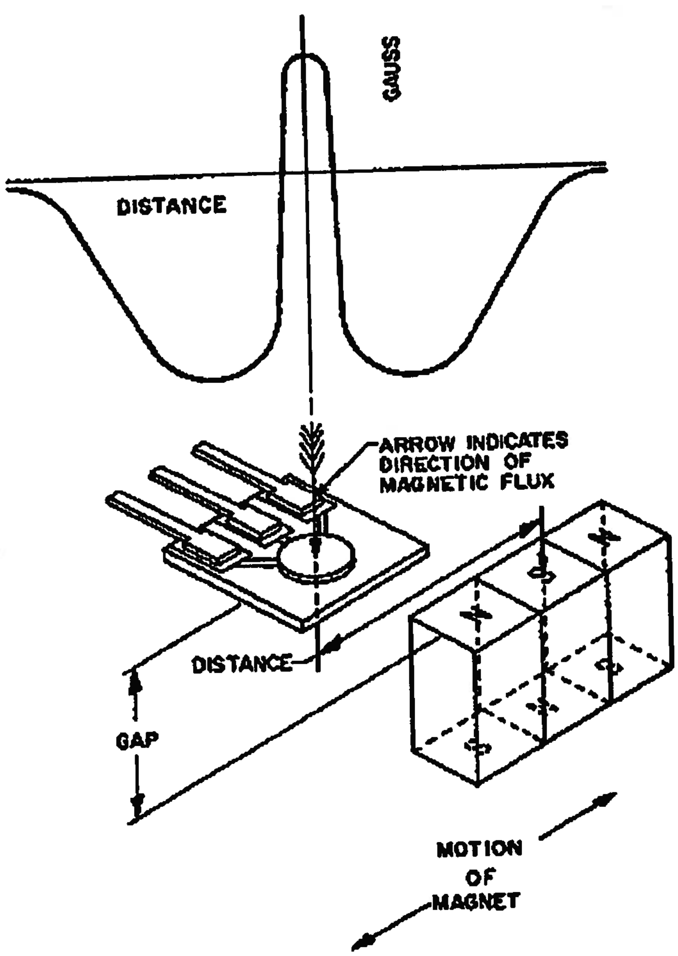


Fig 2 : Various Experimental Configurations and resulting plots

2.2 The Insect

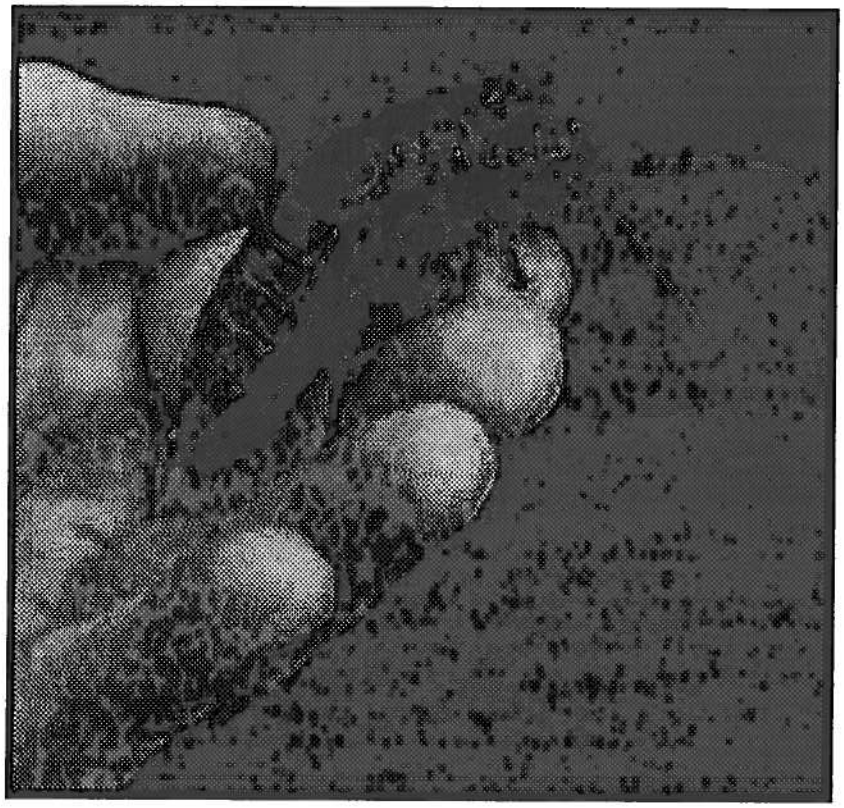


Figure 2: Madagascan Giant Hissing Cockroach

For this experiment, Madagascan Giant Hissing Cockroaches were used as the source of heartbeat. These insects are very convenient for several reasons. Before mentioning these, an explanation of the vascular system of insects in general will provide some interesting information as to *why* we can detect a movement in the first place.

Unlike mammals (where blood is confined to veins/arteries) the circulatory system of an insect is *open* [1]. The main (and often only) blood vessel is located dorsal to the alimentary tract and extends through the thorax and abdomen. Elsewhere however, the blood flows unrestricted throughout the body cavity. Consider Fig.3, which is a cross section of the thorax of insects in general. Most of what is labeled on this diagram is unimportant to this experiment – the point of including this diagram is to illustrate that there is essentially *nothing* in the body cavity of an insect except a small central section provided for the gut. Hence we do not have to search for a vein or artery with sufficient pressure to shift a small magnet affixed above the position. Instead, freely flowing blood has the effect of turning the entire insect's body into one giant pressure point. Combined with the fact that the dorsal (upper) exoskeleton of cockroaches is a *single* fused shell, the heartbeat is relatively easy to detect anywhere on the dorsal surface of the insect.

[1] All information and diagrams taken from [1][page 96-99]

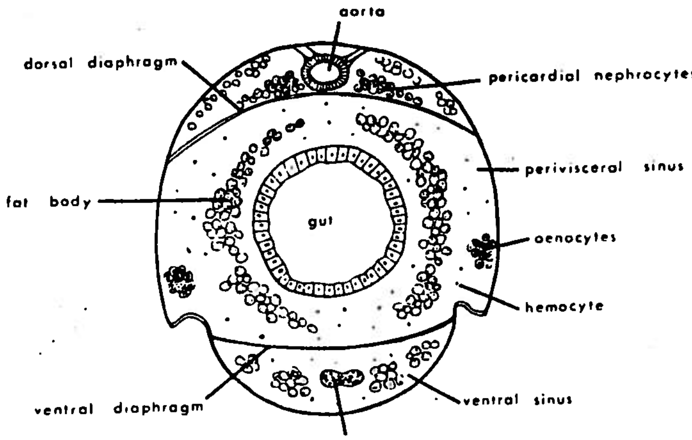


FIGURE 3: Cross section of Thorax

Several other features of cockroaches make them convenient for use in this experiment. A major characteristic is that the heart of a cockroach is located directly under the dorsal surface. Thus, as Fig.4 illustrates, a magnet affixed to the dorsal surface has *nothing* between it and the beating heart with the exception of a thin layer of exoskeleton.

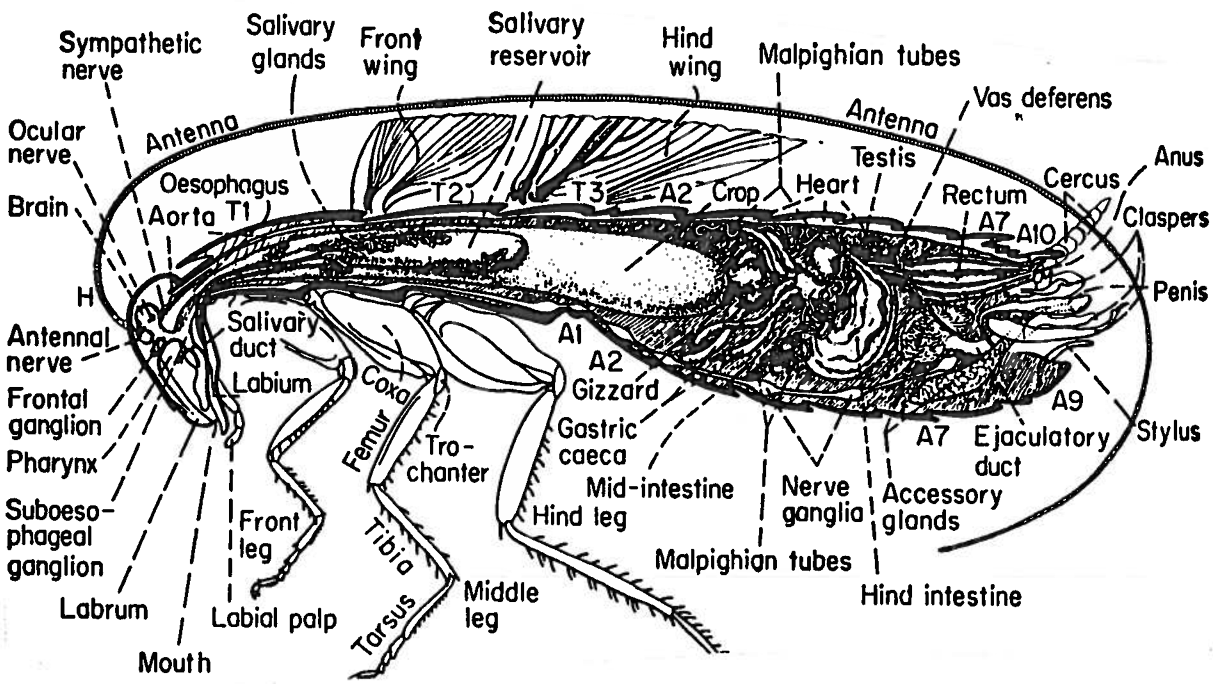


FIGURE 4: Anatomy of a cockroach

The final characteristic considered in the choice of cockroaches as subjects was that they are known to be relatively slow moving – especially the Madagascan species. However, this characteristic turned out to be of no particular use. This was because the phrase *slow – moving* described the actual locomotion of the insect. The *movement* of the insect could simply not be considered slow by any means! Getting the cockroaches to stop fidgeting long enough for a detection run proved to be a patience-inspiring experience. Lighting was thought to play an important role, but had a double-negative effect: if the overhead lights were left on, the roaches fidgeted due to the discomfort of not being in a dark place. When the lights were turned off, the nocturnal tendencies of the roaches came to life and they seemed very happy attempting to climb out of the petrie dish and wander about the walls of Brock University. Cooling the insects down with refrigeration

2.3 The circuit

Note: a diagram of the complete circuit immediately follows this page.

A HET records all magnetic fields, including the earths. This indiscriminateness means that the detector will always produce a large constant signal created by the earth and the magnet. When originally assembling the circuit, it was not yet known what quantitative dimensions the final voltage values were going to have. Since the earth's magnetic field produced approx +5V output, and the lab equipment had a ±15V range, this only left a ±20 V differential range to work with. Although this proved to be more than ample, this was not known in the beginning. Thus, some means of balancing the voltage offset caused by the earth's magnetic field was included in the circuit. Adjusting the offset to zero allowed the use of the full ±30 V range of the equipment. This adjustment was made with a potentiometer-based addition to the circuit (see Fig.5).

On top of the voltage constant produced by the earth, the magnet's motion created a small changing signal. A single op-amp cannot accurately amplify a small signal on top of a voltage constant. For this, an instrumentation amplifier was used. The resistor values were chosen to give this portion of the circuit a gain of 50. [2]

It is important to note that the chips used in this circuit are semiconductor devices – they're not perfect. Hence the instrumentation amplifier itself produced some offset on its output. To account for this, another potentiometer-based addition was made to the circuit. It was important to note that in the final output, adjusting this potentiometer did not have a drastic effect. Quite possibly, this entire portion of the circuit can be removed.

Immediately after the instrumentation amplifier, two op-amps were added to provide for more gain. Using 10kΩ resistors, this gave a final gain of 5000.

At this gain, the heartbeat *was* detected. However, the resulting graph proved to be a very noisy signal. To clean this up, a low-pass filter was added to the circuit. To be more specific, a sequential RC filter was employed. This means connecting two (or more) single-pole RC filters in sequence, using the output of one to drive the next [4][page 110]. Unfortunately no calculations were made in determining the values of the resistors and capacitors to use in this section of the circuit. The addition was taken from a schematic diagram for a similar circuit [2][page 98] and happened to work very well on the first try. However, from this we *can* determine the subsequently filtered frequency as follows.

$$\begin{aligned} \omega_L &= \frac{1}{R_1 C_1} \\ 2\pi f &= \frac{1}{R_1 C_1} \\ f &= \frac{1}{2\pi} \times \frac{1}{100k\omega \ \times \ 0.01\nu F} \\ f &= 160\ Hz \end{aligned}$$

It is acknowledged that a more appropriate means of determining values for use in the filter would have been by using Fourier transform analysis. This would have allowed the troublesome noise frequency to be determined, and thus the source could be physically isolated from the experimental setup.

[2]The gain of both the instrumentation amplifier and the op-amps was determined using standard gain formulas from Faissler [3][pages 284, 250]

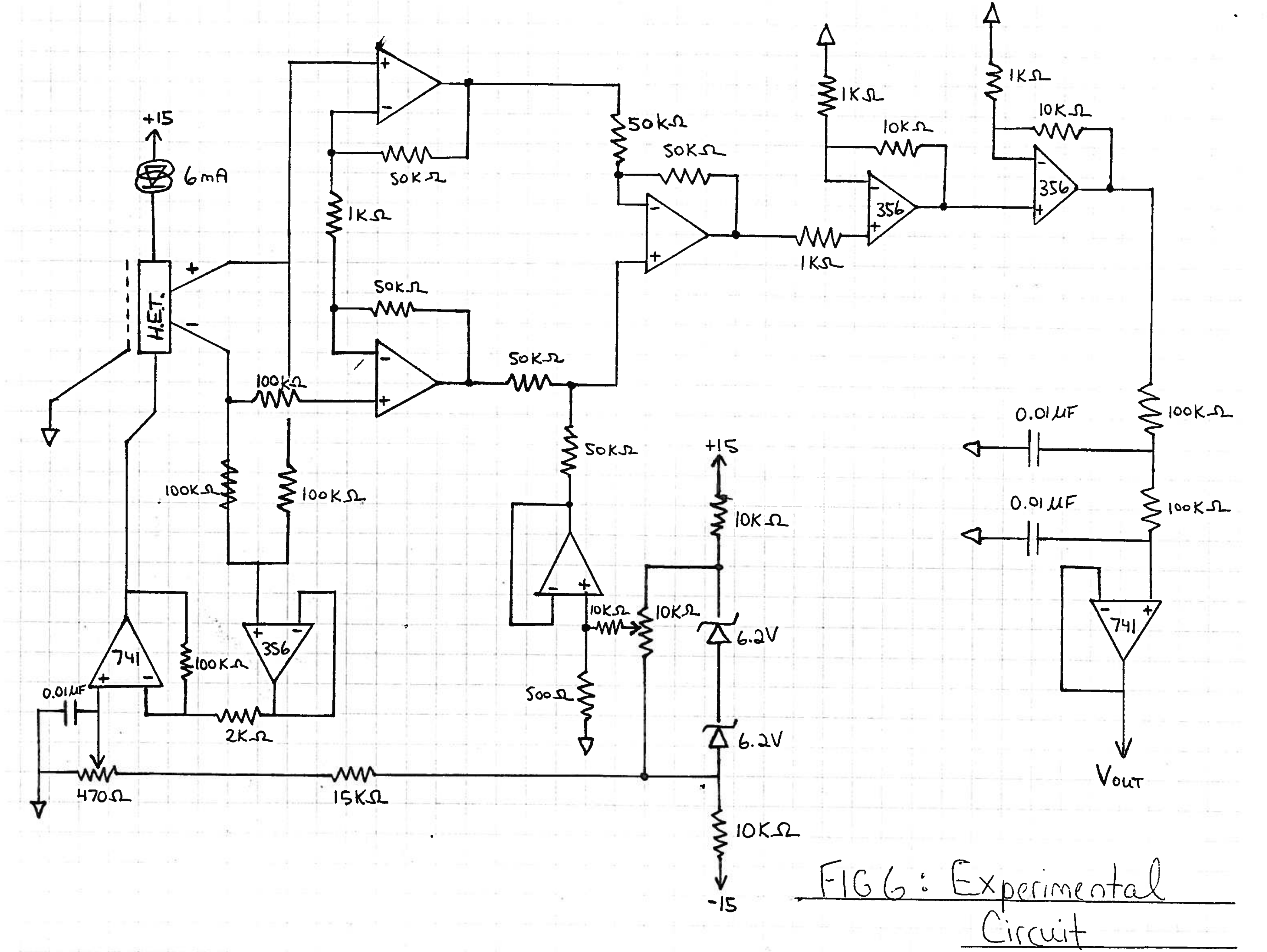


FIG 6: Experimental Circuit

3 Experimental

The basic setup for this lab is as follows, pictured in Fig.6.

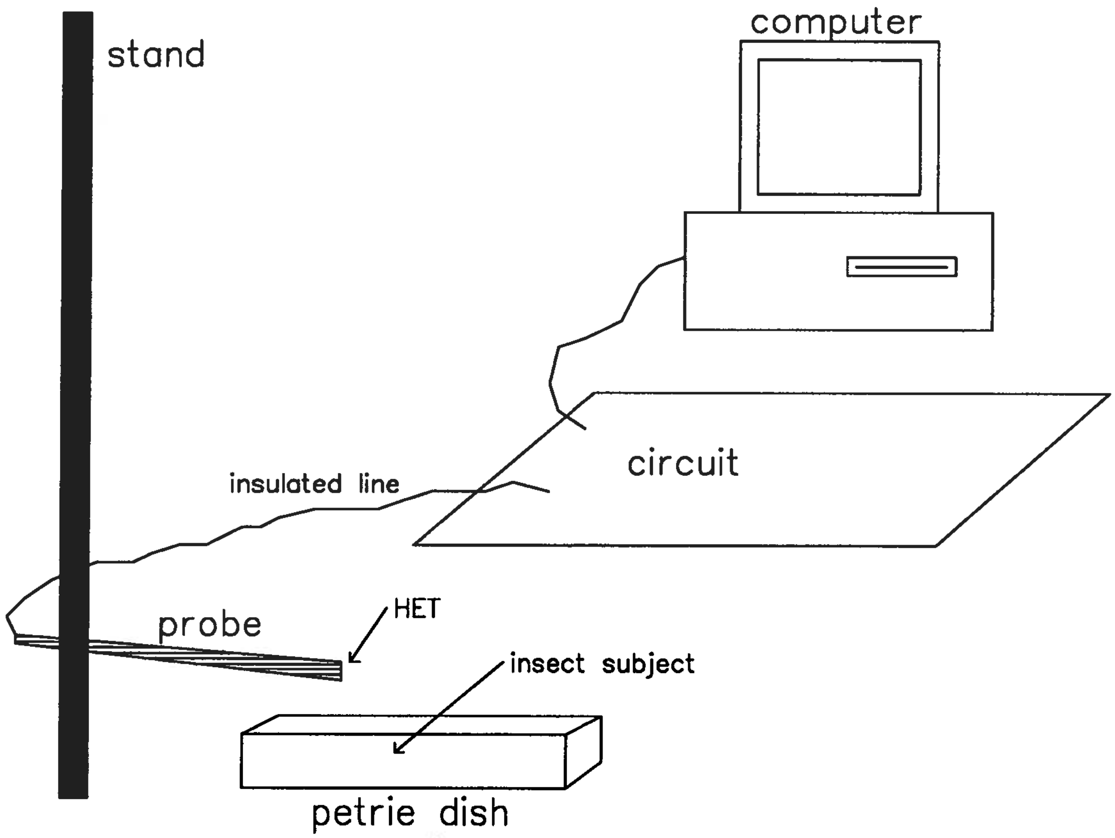


Figure 7: Experimental Setup

It was suggested that the lights be turned out to avoid extraneous noise production in the circuit. This was attempted and had virtually no effect. Also, to account for any noise produced by the long leads going from the probe to the circuit, extra care was taken in insulating this line [3]. This mainly consisted of wrapping the four wires from the HET together, surrounding the whole bundle with aluminum foil, and grounding the entire package.

The resulting output voltage was fed into the analog-to-digital converter of the PCLAB board and graphically displayed on the screen using the PCLAB program. This allowed for $on - the - spot$ graphical analysis rather than taking the data to another computer and running Physica [4].

[3]This was performed by staff of Brock's Electronic Shop, whom I greatly acknowledge.

[4]At the time Exceed was not operating properly to allow Physica to be launched from the lab, and the experimenter had no knowledge of Gnuplot

4 Results

Recall that when the heartbeat was initially detected, there was no low-pass filter addition in the circuit. It was at this point that the first somewhat useful data run was performed, and the result is shown in Fig.7 below. One can clearly see the need for filtering.

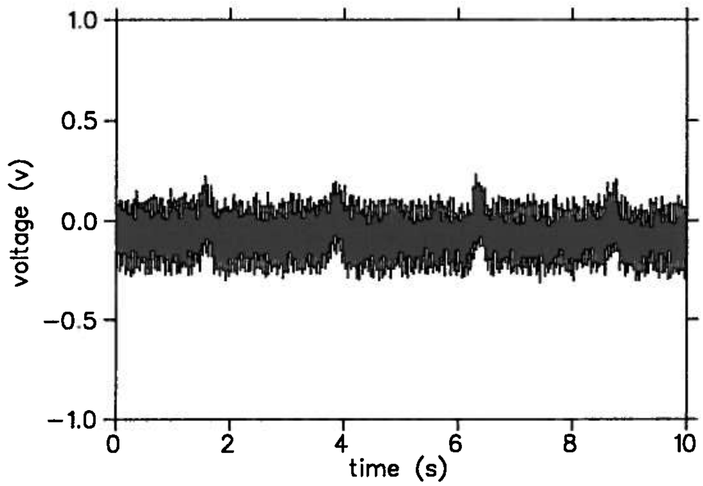


Figure 8: Signal before low-pass filtering

At this point in the experiment, it was guessed that the heartbeat signal was much more prominent than what Fig.7 implies. Quite possibly the majority of the signal was being masked by noise and only the upper portion of the peak was exposing itself. Thus the need for filtering was vital. After setting up the low-pass filter, a *much* cleaner signal was collected, and is displayed in Fig.8.

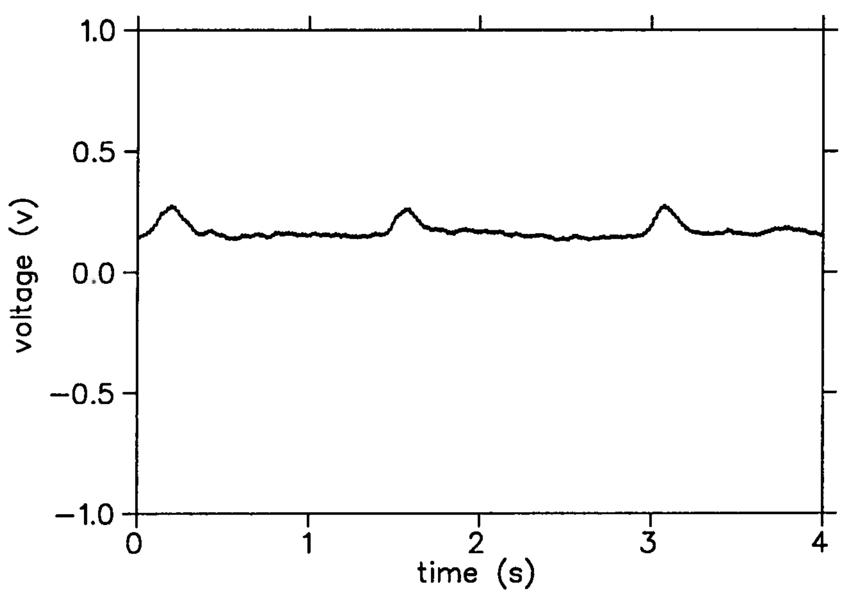


Figure 9: Signal after low-pass filtering

Notice that the rate of the heartbeat seems to contradict what one might expect when considering the size of the animal. It is a well-known fact that smaller animals typically have heartbeat rates that increase with a decrease in body size. A gerbil, for example, has a pulse that is so fast it is difficult to discern individual beats when holding onto the animal [1][page 3]. However, it is obvious from Fig.8 that this rule does not apply to all animals – perhaps only those of the mammal kingdom.

The most interesting observation made in this experiment was the result of stimulating the cockroach's antennae. Readings were taken simultaneously during this period and resulted in the graph shown in Fig.9.

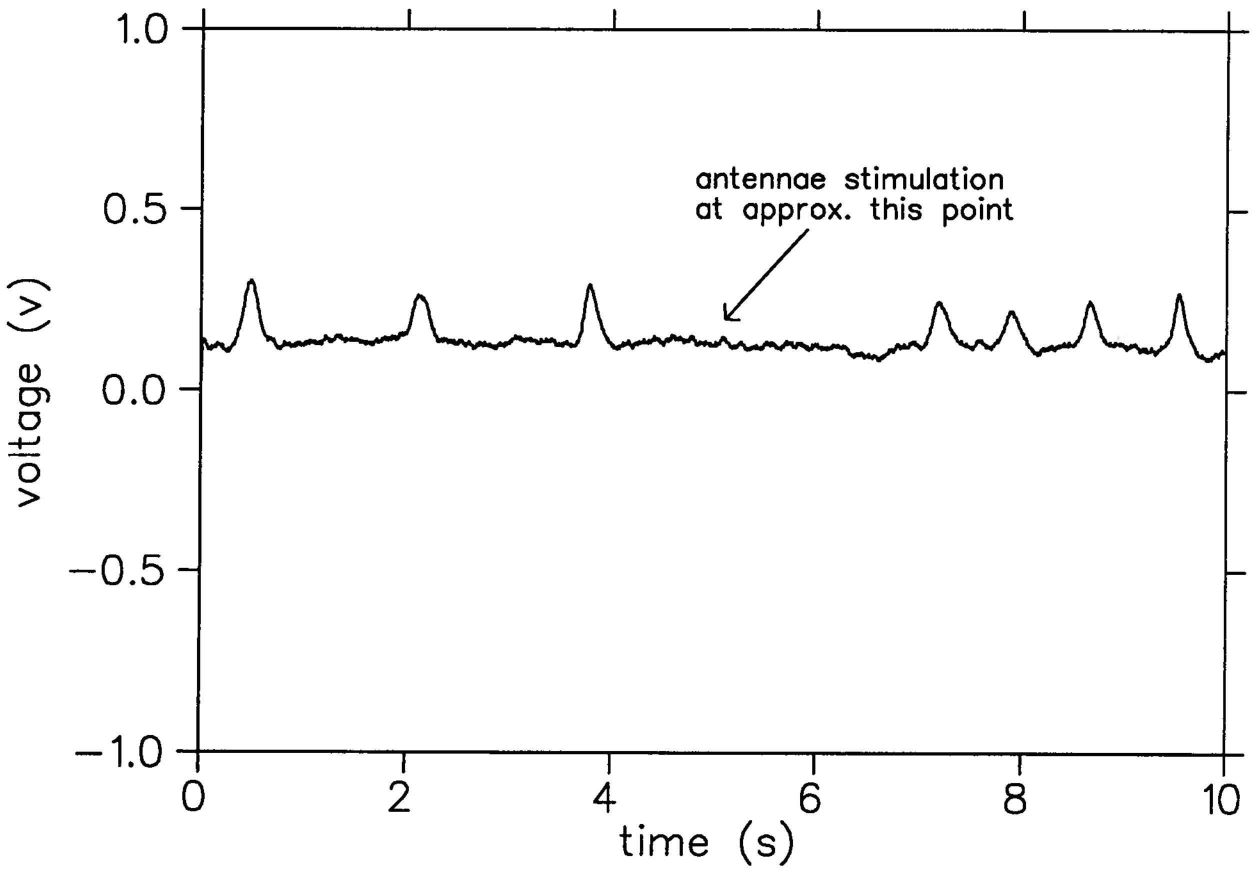


Figure 10: Signal while touching insect antennae

Note that the cockroach apparently skips a beat at the 5 second mark – exactly corresponding to the moment the antennae was stimulated. Furthermore, when the heartbeat returned, there was an increase in the rate as we might expect. In a sense, the insect had been frightened and perhaps released hormones or endorphins (equivalent to a human release of adrenaline) in an attempt to speed up the animal's metabolism to aid in escaping – a natural predatorial mechanism.

As a final investigation, the cockroach was placed in a refrigerator for 15 minutes. This was an attempt to see if the heartbeat could also be reduced. The results of this are shown in Fig.10.

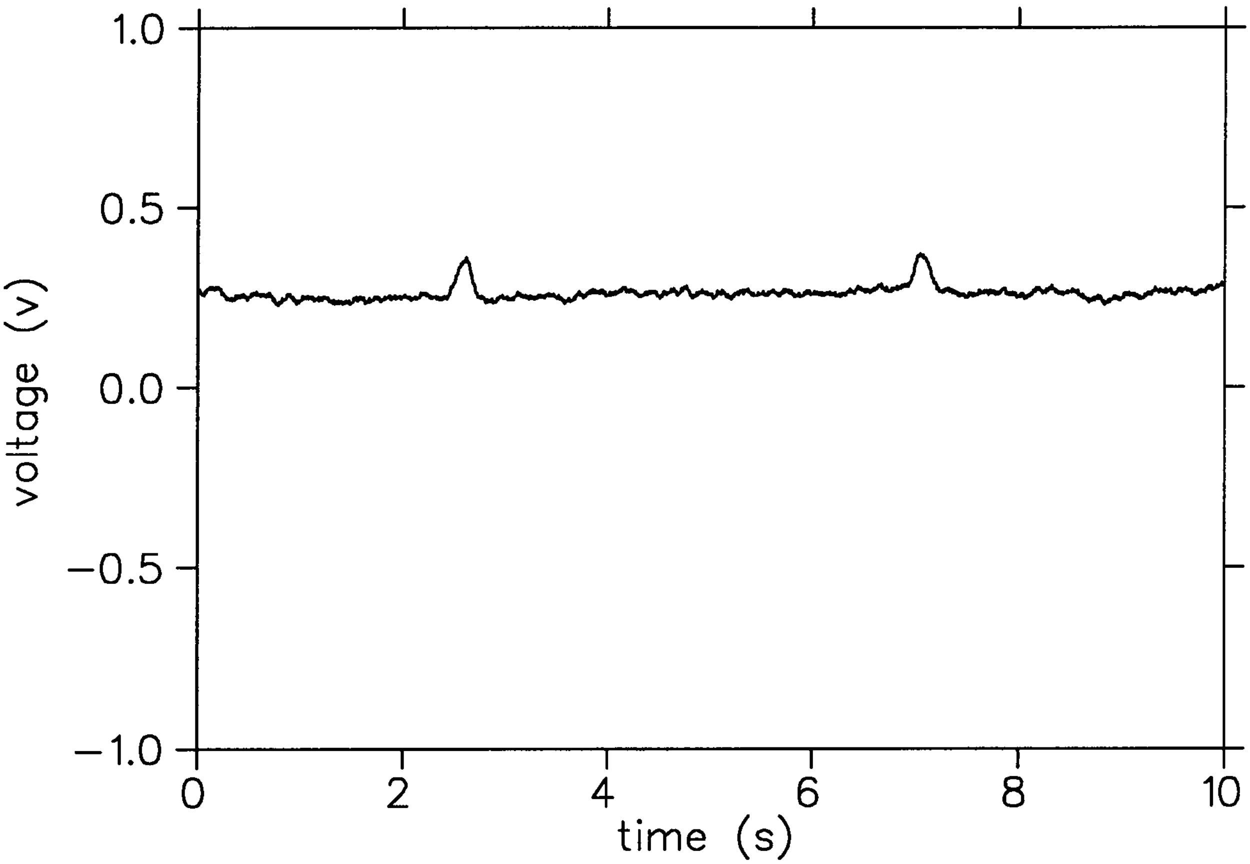


Figure 11: Signal after 15 min of refrigeration

Clearly the metabolism of the insect has experienced quite a slowdown – it has, in effect, been halved. Instead of 4-5 beats per second the cockroach displayed only 2 beats every ten seconds after being subjected to cooler temperatures for 15 minutes. It would be interesting to see if the heart rate could be reduced even further – say to the order of 1-2 beats per *minute*. Ethically however, Brock's Biology department would not simply not allow for this type of experimentation.

5 Conclusion

To quantify some of the findings in this experiment, it was determined that the average heart rate of a Madagascan Giant Hissing Cockroach is approximately 4-5 beats every ten seconds. As expected, the heart rate can rise or fall depending on environmental conditions such as stress and changing temperature exposure.

It was also concluded that the magnitude of the affective output voltage in this setup could be adjusted by changing the distance between the magnet and the HET. No changes in the circuit had to be made after initially assembling it. The gain and the resistor values proved to be quite ample, and if data runs proved to be rather useless, changes were made in the setup of the probe and magnet rather than within the circuit itself.

The true beauty of this experiment, however, was not the pattern of heartbeats detected, or how different independent variables such as temperature and stress affected them, but rather in the fact that the beat itself was *even detectable*. To take such an incredibly small signal and amplify it using an electronic circuit is not only the conclusion of this experiment, but the ultimate conclusion of this entire course. From start to finish, PHYS 3P92 has been about teaching us how to use electronics to enhance the data collection routine in a Physics laboratory. Certainly the concepts learned in this investigation have done just that. To take a magnet and attach it to an insect, amplify the micron-sized distance change that the magnet experiences, and take over 4000 voltage readings in the space of 10 seconds, is truly impossible by unaccomodated human standards. However, with the use of electronic circuits and computers, these impossibilities become realities. There is most definitely some limitations, but with proper adjustment of the equipment and proper use of certain electronic *tricks* (eg. filtering) even these limitations can be overcome to a satisfactory degree.

References

[1] Z. Caldwell *Insect Anatomy.* Freeman Publishing, 1994.

[2] S. Carlson. *Detecting Micron Size Movements.* Scientific American, August 1996.

[3] W. L. Faissler. *An Introduction to Modern Electronics.* John Wiley and Sons, 1991.

[4] L. R. Fortney. *Principles of Analog and Digital Electronics.* Harcourt Publishing, 1987.

[5] J. Lighton *Hall Effect Transducers.* www.theshere.com/SAS/